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Request for grant of a patent

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| | | |
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| 1. | Your reference | MPC/9221 GB |
| 2. | Patent application number *(The Patent Office will fill in this part)* | 20 DEC 2002 0229826.3 |
| 3. | Full name, address and postcode of the or of each applicant *(underline all surnames)* | BlazePhotonics Limited<br>Finance Office, University of Bath<br>The Avenue, Claverton Down<br>Bath<br>BA2 7AY |
| | Patents ADP number *(if you know it)* | 08141129001 |
| | If the applicant is a corporate body, give the country/state of its incorporation | United Kingdom |
| 4. | Title of the invention | Enhanced Photonic Bandgap Waveguide |
| 5. | Name of your agent *(if you have one)* | Abel & Imray |
| | "Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)* | 20 Red Lion Street<br>London<br>WC1R 4PQ |
| | Patents ADP number *(if you know it)* | 174001 |
| 6. | If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number | Country / Priority application number *(if you know it)* / Date of filing *(day/month/year)* |
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DUPLICATE



# Enhanced Optical Waveguide

(Ref: 0065)

## Technical Field

The present invention is in the field of optical waveguides and relates in particular to optical waveguides that guide light by virtue of a photonic bandgap.

## Background Art

Optical fibre waveguides, which are able to guide light by virtue of a so-called photonic bandgap (PBG), were first proposed in 1995.

In, for example, "Full 2-D photonic bandgaps in silica/air structures", Birks et al., Electronics Letters, 26 October 1995, Vol. 31, No. 22, pp.1941-1942, it was proposed that a PBG may be created in an optical fibre by providing a dielectric cladding structure, which has a refractive index that varies periodically between high and low index regions, and a core defect in the cladding structure in the form of a hollow core. In the proposed cladding structure, periodicity was provided by an array of air holes that extended through a silica glass matrix material to provide a PBG structure through which certain wavelengths of light could not pass. It was proposed that light coupled into the hollow core defect would be unable to escape into the cladding due to the PBG and, thus, the light would remain localised in the core defect.

It was appreciated that light travelling through a hollow core defect, for example filled with air or even under vacuum, would suffer significantly less from undesirable effects, such as non-linearity, loss and dispersion, compared with light travelling through a solid silica or doped silica fibre core. As such, it was appreciated that a PBG fibre may find application as a transmission fibre to transmit light over extremely long distances, for example across the Atlantic Ocean, without undergoing signal regeneration or as a high optical power delivery waveguide. In contrast, for standard index-guiding, single mode optical fibre, signal regeneration is typically required approximately every 80 kilometres.

The first PBG fibres that were attempted by the inventors had a periodic cladding structure formed by a triangular lattice of circular air holes embedded in a solid silica matrix and surrounding a central air core defect. Such fibres were formed by stacking circular or hexagonal capillary tubes, incorporating a core defect into the cladding by omitting a central capillary of the stack, and then heating and drawing the stack, in a one or two step process, to

form a fibre having the required structure. The first fibres made by this process had a core defect formed by the omission of a single capillary from the centre of the cladding structure.

International patent application PCT/GB00/01249 (The Secretary of State for Defence, UK), filed on 21 March 2000, proposed the first PBG fibre to have a so-called seven-cell core defect, surrounded by a cladding comprising a triangular lattice of air holes embedded in an all-silica matrix. The core defect was formed by omitting an inner capillary and, in addition, the six capillaries surrounding the inner capillary. This fibre structure was seen to guide one or two modes in the core defect, in contrast to the previous, single-cell core defect fibre, which appeared not to support any guided modes in the core defect.

According to PCT/GB00/01249, it appeared that the single-cell core defect fibre, by analogy to the density-of-states calculations in solid-state physics, would only support approximately 0.23 modes. That is, it was not surprising that the single-cell core defect fibre appeared to support no guided modes in its core defect. In contrast, based on the seven-fold increase in core defect area (increasing the core defect radius by a factor of $\sqrt{7}$), the seven-cell core defect fibre was predicted to support approximately 1.61 spatial modes in the core defect. This prediction was consistent with the finding that the seven-cell core defect fibre did indeed appear to support at least one guided mode in its core defect.

A preferred fibre in PCT/GB00/01249 was described as having a core defect diameter of around 15μm and an air-filling fraction (AFF) – that is, the proportion by volume of air in the cladding - of greater than 15% and, preferably, greater than 30%.

In "Analysis of air-guiding photonic bandgap fibres", Optics Letters, Vol. 25, No. 2, January 15, 2000, Broeng et al. provided a theoretical analysis of PBG fibres. For a fibre with a seven-cell core defect and a cladding comprising a triangular lattice of near-circular holes, providing an AFF of around 70%, the structure was shown to support one or two air guided modes in the core defect. This was in line with the finding in PCT/GB00/01249.

In the chapter entitled "Photonic Crystal Fibers: Effective Index and Band-Gap Guidance" from the book "Photonic Crystal and Light Localization in the 21$^{st}$ Century", C.M. Soukoulis (ed.), ©2001 Kluwer Academic Publishers, the authors presented further analysis of PBG fibres based primarily on a seven-cell core defect fibre. The optical fibre was fabricated by stacking and drawing hexagonal silica capillary tubes. The authors suggested that a core defect must be large enough to support at least one guided mode but that, as in conventional fibres, increasing the core defect size would lead to the appearance of higher order modes. The authors also went on to suggest that there are many parameters that can

have a considerable influence on the performance of bandgap fibres: choice of cladding lattice, lattice spacing, index filling fraction, choice of materials, size and shape of core defect, and structural uniformity (both in-plane and along the axis of propagation).

WO 02/075392 (Corning, Inc.) identifies a general relationship in PBG fibres between the number of so–called surface modes that exist at the boundary between the cladding and core defect of a PBG fibre and the ratio of the radial size of the core defect and a pitch of the cladding structure, where pitch is the centre to centre spacing of nearest neighbour holes in the triangular lattice of the exemplified cladding structure. It is suggested that when the core defect boundary, together with the photonic bandgap crystal pitch, are such that surface modes are excited or supported, a large fraction of the "light power" propagated along the fibre is essentially not located in the core defect. Accordingly, while surface states exist, the suggestion was that the distribution of light power is not effective to realise the benefits associated with the low refractive index core defect of a PBG crystal optical waveguide. The mode energy fraction in the core defect of the PBG fibre was shown to vary with increasing ratio of core defect size to pitch. In other words, it was suggested that the way to increase mode energy fraction in the core defect is by decreasing the number of surface modes, in turn, by selecting an appropriate ratio of the radial size of the core defect and a pitch of the cladding structure. In particular, WO 02/075392 states that, for a circular core structure, a ratio of core radius to pitch of around 1.07 to 1.08 provides a high mode power fraction of not less than 0.9 and is single mode. Other structures are considered, for example in Figure 7, wherein the core defect covers an area equivalent to 16 cladding holes.

In a Post-deadline paper presented at ECOC 2002, "Low Loss (13dB) Air core defect Photonic Bandgap Fibre", N. Venkataraman et al. reported a PBG fibre having a seven-cell core defect that exhibited loss as low as 13dB/km at 1500nm over a fibre length of one hundred metres. The structure of this fibre closely matches the structure considered in the book chapter referenced above. The authors attribute the relatively small loss of the fibre as being due to the high degree of structural uniformity along the length of the fibre.

PBG fibre structures are typically fabricated by first forming a pre-form and then heating and drawing an optical fibre from that pre-form in a fibre-drawing tower. It is known either to form a pre-form by stacking capillaries and fusing the capillaries into the appropriate configuration of pre-form, or to use extrusion.

For example, in PCT/GB00/01249, identified above, a seven-cell core defect pre-form structure was formed by omitting from a stack of capillaries an inner capillary and, in

addition, the six capillaries surrounding the inner capillary. The capillaries around the core defect boundary in the stack were supported during formation of the pre-form by inserting truncated capillaries, which did not meet in the middle of the stack, at both ends of the capillary stack. The stack was then heated in order to fuse the capillaries together into a pre-form suitable for drawing into an optical fibre. Clearly, only the fibre drawn from the central portion of the stack, with the missing inner seven capillaries, was suitable for use as a hollow core defect fibre.

US patent application number US 6,444,133 (Corning, Inc.), describes a technique of forming a PGB fibre pre-form comprising a stack of hexagonal capillaries in which the inner capillary is missing, thus forming a core defect of the eventual PBG fibre structure that has flat inner surfaces. In contrast, the holes in the capillaries are round. US 6,444,133 proposes that, by etching the entire pre-form, the flat surfaces of the core defect dissolve away more quickly than the curved surfaces of the outer capillaries. The effect of etching is that the edges of the capillaries that are next to the void fully dissolve, while the remaining capillaries simply experience an increase in hole-diameter. Overall, the resulting pre-form has a greater fraction of air in the cladding structure and a core defect that is closer to a seven-cell core defect than a single cell core defect.

PCT patent application number WO 02/084347 (Corning, Inc.) describes a method of making a pre-form comprising a stack of hexagonal capillaries of which the inner capillaries are preferentially etched by exposure to an etching agent. Each capillary has a hexagonal outer boundary and a circular inner boundary, as illustrated in the diagram in Figure 10 herein. The result of the etching step is that the centres of the edges of the hexagonal capillaries around the central region dissolve more quickly than the corners, thereby causing formation of a core defect. In some embodiments, the circular holes are offset in the inner hexagonal capillaries of the stack so that each capillary has a wall that is thinner than its opposite wall. These capillaries are arranged in the stack so that their thinner walls point towards the centre of the structure. An etching step, in effect, preferentially etches the thinner walls first, thereby forming a seven-cell core defect.

## Disclosure of the Invention

According to a first aspect, the present invention provides a photonic bandgap structure, having a plane cross section and a length dimension that extends perpendicular to the plane cross section, the photonic bandgap structure, in the plane cross section, comprising

a substantially periodic array of relatively low refractive index regions, being separated from one another by relatively high refractive index regions, which extend along the photonic bandgap structure in the length dimension, the array having a characteristic primitive unit cell and a pitch; and

a core defect, surrounded by the photonic bandgap structure, the core defect comprising a region of relatively low refractive index having a plane cross section and a length dimension that extends perpendicular to the plane cross section, said plane cross section and length dimension being parallel to the same dimensions of the photonic bandgap structure, the core defect having an area which is greater than sixteen times the area of a primitive unit cell.

Hitherto, the prior art teachings relating to PBG fibres have focused on a core defect that is just large enough to support a single mode, but not so large that it supports additional, unwanted modes. In practice, in the prior art, the preferred core defect size for fibres that have actually been made has generally been selected to be larger than a single unit cell but no larger than about the size of seven inner most capillaries, or unit cells, in a triangular lattice of capillaries.

As will be described herein, the present inventors have demonstrated that increasing the core defect size beyond sizes proposed in the prior art teachings may provide significant benefits, which potentially outweigh the perceived or actual disadvantages of doing so.

The present inventors also demonstrate that at least some of the perceived disadvantages of increasing the core defect size, based on well-understood theory for index-guiding fibres, do not necessarily apply in the case of PBG fibres. In addition, the present inventors propose that, to the extent certain perceived disadvantages of increasing the core defect size do exist, there are ways to mitigate these effects by careful design of the PBG fibre structure. A number of possible ways to mitigate such effects will be considered. In particular, the inventors demonstrate that the number and kinds of modes that are supported by a PBG fibre are not determined only by the diameter of the core defect, an index difference between a core and cladding and wavelength of light, unlike in a conventional index-guiding fibre. Indeed, the present inventors demonstrate herein that it is possible to increase the diameter of the core defect significantly without proportionately increasing the numbers of modes supported by the PBG fibre.

It is highly unlikely in practice that a photonic bandgap structure according to the present invention will comprise a 'perfectly' periodic array, due to imperfections being

introduced into the structure during its manufacture and/or perturbations being introduced into the array by virtue of the presence of the core defect. The present invention is intended to encompass both perfect and imperfect structures. Likewise, any reference to "periodic", "lattice", or the like herein, imports the likelihood of imperfection.

As is well-known, a periodic, two-dimensional array, or lattice, can be defined by a unit cell, which has a translational symmetry such that it can tile over the entire array. A unit cell is said to be 'primitive' if it cannot itself be broken down into smaller unit cells.

A photonic bandgap structure as described herein typically has two-dimensional translational symmetry, in the plane cross-section, and is homogenous in the length direction. An exemplary primitive unit cell of a photonic bandgap structure can been seen in Figure 10, which illustrates a fibre preform comprising hexagonal capillaries 1005 arranged to form, on a macro-scale, a photonic bandgap structure around a core defect 1025. Referring to Figure 10, it can be seen that a single capillary 1005 can be tiled over the entire photonic bandgap structure, by translations in the x (or horizontal) direction, and translations at 30 degrees to the y (or vertical) direction. As such, a single capillary is an example of a primitive unit cell of the structure of Figure 10. Of course, the structure has an infinite number of other primitive unit cells, which have in common the same size and shape as a single capillary but are centred on a different part of the structure. For example, another primitive unit cell has its centre at the locus of three neighbouring capillaries (e.g. point 1015) for the structure in Figure 10.

The term "primitive unit cell" is not used herein in its strict sense since, as already stated, a practical photonic bandgap structure is unlikely to be 'perfect' in form due to manufacturing imperfections and/or perturbations due to the presence of the core defect. Accordingly, a primitive unit cell of such a structure is likely to be at best only a close approximation to a primitive unit cell of an intended, perfect structure; and the term primitive unit cell is intended herein to cover such close approximations.

The core defect may comprise an area that is large enough to contain at least sixteen whole primitive unit cells. Such an area would have to include sixteen whole primitive unit cells but, in addition, could include any number of partial primitive unit cells. Accordingly, the area could be significantly larger than an area which is only sixteen times the area of a primitive unit cell, which could be made from either or both whole and partial primitive unit cells. The core defect may comprise an area that is substantially equal to nineteen times the area of a primitive unit cell. The core defect may comprise an area that is large enough to contain at least nineteen whole primitive unit cells.

The core defect region may have at least two-fold rotational symmetry. For example, the core region may be elongate, triangular, square, hexagonal, octagonal, dodecagonal or even circular. Alternatively, the core defect may have no rotational symmetry or may be irregular or even random in form.

In preferred embodiments of the present invention, the relatively low refractive index regions are arranged in an array, for example a triangular array. The primitive unit cell may be centred on a single relatively low refractive index region, that being the largest relatively low refractive index region in the primitive unit cell. In principle, a primitive unit cell may comprise various sizes of relatively low refractive index region, for example, as a result of interstitial holes forming between regions of relatively low index and relatively high index. In general, though, different sizes of low index and/or high index regions may be included within a primitive unit cell of the photonic bandgap structure.

The core defect may comprise an area substantially equal to the area of a first primitive unit cell, a first group of all primitive unit cells that surround the first primitive unit cell and a second group of all primitive unit cells that surround said first group of primitive unit cells. In a triangular array, for example, the first group would comprise six primitive unit cells and the second group would comprise twelve primitive unit cells.

The core defect may have resulted from omission or removal of relatively high refractive index regions from a first primitive unit cell, a first group of all primitive unit cells that surrounded the first primitive unit cell and a second group of all primitive unit cells that surrounded said first group of primitive unit cells. In practice, such omission or removal would take place at the stage of forming a preform rather than during or after a fibre had been drawn from a preform. For example, where the primitive unit cells are glass capillaries, removal or omission of a relatively high index region would be equivalent to removing or omitting a capillary. However, for example, where relatively low index regions comprise a fluid (other than air) or a solid material, removal of relatively high index regions could be equivalent to replacing the those regions with additional relatively low index material. Even though such a core defect may result from omission or removal of a fixed number of primitive unit cells, or respective relatively high index material, on a macro scale (for example in a preform), the area of the core defect in a final fibre structure may, on average, scale differently to the photonic bandgap structure as a result of the fabrication process. Accordingly, the core defect area in a final fibre structure may be, proportionately, larger or smaller than it was on the macro scale. For example, for a given number of missing or

omitted primitive unit cells, significant variations in core defect diameter can result from pressurising the core defect to different pressures during a heating and drawing a preform step of production.

According to a second aspect, the present invention provides a photonic bandgap optical waveguide comprising:

a photonic bandgap structure, having a plane cross section and a length dimension that extends perpendicular to the plane cross section, the photonic bandgap structure, in the plane cross section, comprising a substantially periodic array of relatively low refractive index regions, being separated from one another by relatively high refractive index regions, which extend along the photonic bandgap structure in the length dimension, the array having a characteristic primitive unit cell and a pitch, the primitive unit cell being centred on a single relatively low refractive index region, that being the largest relatively low refractive index region in the primitive unit cell; and

a core defect, surrounded by the photonic bandgap structure, the core defect comprising a region of relatively low refractive index having a plane cross section and a length dimension that extends perpendicular to the plane cross section, said plane cross section and length dimension being parallel to the same dimensions of the photonic bandgap structure, wherein the core defect resulted from omission or removal of relatively high refractive index regions from a first primitive unit cell, a first group of all primitive unit cells that surrounded the first primitive unit cell and a second group of all primitive unit cells that surrounded said first group of primitive unit cells.

The photonic bandgap structure may comprise a substantially periodic, triangular array of relatively low refractive index regions. Then, the core defect may result from omission or removal of relatively high refractive index regions from a first primitive unit cell, the six primitive unit cells that surround the first primitive unit cell and the twelve primitive unit cells that surround said six primitive unit cells.

In preferred embodiments of the present invention, the relatively low refractive index regions are separated from one another by relatively high refractive index veins that are joined at nodes.

Preferably, at least some of the nodes within the photonic bandgap structure have diameters that are significantly larger than the thickness of the veins that meet at the nodes. More preferably, substantially all of the nodes within the photonic bandgap structure have diameters that are significantly larger than the thickness of the veins that meet at the nodes.

In preferred embodiments of the present invention the waveguide further comprises, in the plane cross section, a boundary at the interface between the core defect and the photonic bandgap structure, the boundary comprising a plurality of relatively high refractive index veins that are joined at nodes.

Preferably, the fraction of nodes which have diameters that are significantly larger than the thickness of the veins that meet at the nodes is less on the boundary than in a similar region of the photonic bandgap structure. For example, the boundary may include substantially no nodes which have diameters that are significantly larger than the thickness of the veins that meet at the nodes.

Preferably, the nodes that are significantly larger than the thickness of the veins that meet at the nodes have a diameter that is at least 1.5 times the thickness of the veins. More preferably, the nodes that are significantly larger than the thickness of the veins that meet at the nodes have a diameter that is at least 2 times the thickness of the veins.

In preferred embodiments of the present invention, at least some of the relatively low refractive index regions are voids filled with air or under vacuum. Additionally, or alternatively, at least some of the relatively high refractive index regions comprise silica glass.

Preferably, the waveguide has an air-filling-fraction that is greater than 80%. The air-filling fraction may be greater than 85%, for example 87.5%.

According to preferred embodiments of the present invention, the waveguide supports a mode in which greater than 98% of the mode power in the waveguide is in relatively low refractive index regions. Preferably, the relatively low refractive index regions comprise air or are under a vacuum. More preferably, the waveguide supports a mode in which greater than 99% of the mode power in the waveguide is in relatively low refractive index regions. Even more preferably, the waveguide supports a mode in which greater than 99.5% of the mode power in the waveguide is in air.

Preferably, the waveguide supports a mode having a mode profile that closely resembles the fundamental mode of a standard, single mode optical fibre. Additionally, said mode preferably supports a maximum amount of the mode power in relatively low refractive index regions compared with other modes that are supported by the waveguide.

According to a third aspect, the present invention provides an optical fibre comprising a waveguide as described above.

According to a fourth aspect, the present invention provides a transmission line for carrying data between a transmitter and a receiver, the transmission line including along at least part of its length the fibre according to the third aspect.

According to a fifth aspect, the present invention provides a preform for making a photonic bandgap optical waveguide, the preform comprising:

a first part for forming a photonic bandgap structure of the photonic bandgap optical waveguide, the first part having a plane cross section and a length dimension that extends perpendicular to the plane cross section and, in the plane cross section, a substantially periodic array of relatively low refractive index regions, being separated from one another by relatively high refractive index regions, which extend along the first part in the length dimension, the array having a characteristic primitive unit cell and a pitch; and

a relatively low-index region which becomes a core defect in the photonic bandgap structure of the photonic bandgap optical waveguide, the relatively low index region being surrounded by said first part and having a plane cross section and a length dimension that extends perpendicular to the plane cross section, said plane cross section and length dimension being parallel to the same dimensions of said first part, the relatively low index region having an area which is greater than sixteen times the area of a primitive unit cell.

According to a sixth aspect, the present invention provides a preform for making a photonic bandgap optical waveguide, the preform comprising:

a first part for forming a photonic bandgap structure of the photonic bandgap optical waveguide, the first part having a plane cross section and a length dimension that extends perpendicular to the plane cross section and, in the plane cross section, a substantially periodic array of relatively low refractive index regions, being separated from one another by relatively high refractive index regions, which extend along the first part in the length dimension, the array having a characteristic primitive unit cell and a pitch, the primitive unit cell being centred on a single relatively low refractive index region and encompassing no more than one relatively low refractive index region; and

a relatively low-index region which becomes a core defect in the photonic bandgap structure of the photonic bandgap optical waveguide, the relatively low index region being surrounded by said first part and having a plane cross section and a length dimension that extends perpendicular to the plane cross section, said plane cross section and length dimension being parallel to the same dimensions of said first part, the core defect resulting from omission or removal of relatively high refractive index regions from a first primitive unit

cell, a first group of all primitive unit cells that surround the first primitive unit cell and a second group of all primitive unit cells that surround said first group of primitive unit cells.

Specific details of preforms according to aspects of the present invention are described below.

According to a seventh aspect, the present invention provides a method of forming a photonic bandgap optical waveguide comprising the steps:

forming a preform stack by stacking a plurality of elongate elements into a periodic, triangular array of elements, the elongate elements comprising a relatively low refractive index elongate inner region enclosed by a relatively high refractive index outer region;

omitting, or substantially removing from an inner region of the stack, a first element, a first number comprising all elements from around said first element and a second number comprising all elements from around said first number of elements; and

heating and drawing the stack, in one or more steps, into a photonic bandgap optical waveguide, characterised by a photonic bandgap structure that surrounds a core defect, the photonic bandgap structure having a plane cross section and a length dimension that extends perpendicular to the plane cross section and comprising, in the plane cross section, a periodic, triangular array of relatively low refractive index regions, being separated from one another by relatively high refractive index regions, which extend along the photonic bandgap structure in the length dimension.

The preform stack may comprise a substantially periodic, triangular array of elongate elements. Then, the inner region of the stack may be formed by omission or substantial removal of a first element, the six elements that surround the first elements and the twelve elements that surround said six elements.

The elements may have a generally hexagonal transverse cross section or a generally circular transverse cross section.

For example, for generally circular cross section elements, when the elements are being stacked, first elongate interstitial voids are formed between elements.

The method may include the additional step of introducing elongate elements into at least some of the first interstitial voids. At least some of the elongate elements may comprise rods. Additionally, or alternatively, at least some of the elongate elements may comprise capillaries. Use of capillaries provides the option to control more closely the volume of glass that is added to an interstitial void for a given outer diameter of capillary. The elongate elements may be introduced into substantially all of the first interstitial voids.

The method may comprise the additional step of introducing a further elongate element into the inner region to support the elements around the inner region. As such, second interstitial voids may be formed between the elements around the inner region and the further elongate element and the method may include the step of introducing elongate elements into at least some of the second interstitial voids. Again, at least some of the elongate elements may comprise rods. Additionally or alternatively at least some of the elongate elements may comprise capillaries.

A reduced fraction of the rods may be introduced into the second interstitial voids compared with the number of rods that are introduced into a similar configuration of first interstitial voids. For example, no elongate elements are introduced into the second interstitial voids.

At least some of the elongate elements that are introduced into the second interstitial voids may have a smaller cross sectional area than the elongate elements that are introduced into the first interstitial voids.

In preferred embodiments of the present invention, the further elongate element has a relatively low refractive index elongate inner region enclosed by a relatively high refractive index outer region, which becomes part of the photonic bandgap optical waveguide.

Alternatively, the further elongate element comprises a material that has a higher coefficient of thermal expansion than the relatively high refractive index material in the elongate elements. Accordingly, the method may comprise the further steps of:

heating the preform stack in order to fuse the elongate elements around the further elongate element;

cooling the preform stack; and

removing the further elongate element from the preform stack prior to heating and drawing the preform stack.

Preferably, at least some of the relatively low refractive index regions comprise air or are under vacuum. Additionally, or alternatively, at least some of the relatively high refractive index regions may comprise silica glass.

According to an eighth embodiment, the present invention provides an optical fibre comprising a photonic bandgap optical waveguide made by the above-described method.

Other aspects and embodiments will become apparent from reading the following description and claims and considering the following drawings.

Brief Description of the Drawings

Embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings, of which:

Figure 1 is a diagram of a transverse cross section of a PBG fibre structure of the kind known from the prior art;

Figure 2 is a diagram which illustrates how various physical characteristics of PBG fibres are defined herein;

Figures 3 and 4 provide diagrams of various examples of PBG fibre structures;

Figures 5 and 6 provide mode spectra plots for the PBG fibre structures of Figures 3 and 4;

Figure 7 provides mode intensity distribution plots for a mode supported by each structure of Figures 3 and 4, which supports the highest amount of light in air;

Figures 8 and 9 provide graphs of mode intensity for x and y axes of the distributions of Figure 7;

Figure 10 is a diagram of a preform suitable for making PBG fibre according to the prior art;

Figure 11 is a diagram of a preform suitable for making a fibre according to embodiments of the present invention; and

Figure 12 is a diagram of an alternative preform suitable for making a fibre according to embodiments of the present invention.

Best Mode For Carrying Out the Invention, & Industrial Applicability

Figure 1 illustrates a transverse cross-section of a fibre structure of the kind described in the prior art. As illustrated, the cladding 100 comprises a lattice of generally hexagonal cells 105, surrounding a seven-cell core defect 110. The core defect has twelve apparent sides – six relatively longer sides and six relatively shorter sides - and is formed by omitting or removing seven central cells; an inner cell and the six cells that surround the inner cell. The cells have typically been removed or omitted from a preform prior to using the preform to make the fibre. As the skilled person will appreciate, although a cell comprises a void, or a hole, for example filled with air or under vacuum, according to the preferred embodiments described herein, the voids or holes may equally be filled with a gas or a liquid or may instead comprise a solid material that has a lower refractive index than the material that surrounds the hole. The material that surrounds the holes is, conveniently, fused, un-doped silica glass.

Two longitudinal planes through the fibre structure of Figure 1 are denoted y and x; with y being a vertical plane passing through the centre of the structure and x being a horizontal plane passing through the centre of the structure as shown.

Hereafter, and with reference to Figure 1, a thin region of glass 115 between any two holes is referred to as a "**vein**" and a region of glass 120 where veins meet is referred to as a "**node**".

The structure also has a core defect boundary 145 comprising the inwardly-facing veins of the cells that surround the core defect 110.

In practice, most of the cladding holes 105 are hexagonal, as shown in Figure 1. The cells around the boundary of the core defect, which are referred to herein as "**boundary cells**", have one of two general shapes. A first kind of boundary cell 125 is generally hexagonal and has an inwardly-facing vein 130 that forms a relatively shorter side of the core defect boundary 145. A second kind of boundary cell 134 has a generally pentagonal form and has an inwardly-facing vein 140 that forms a relatively longer side of the core defect boundary 145.

Figures 2a and 2b are diagrams that illustrate how various dimensions are defined herein for a cladding structure, with reference to four exemplary cladding cells 200. Figure 2a illustrates how the various dimensions of Figure 2b are constructed, whereas Figure 2b illustrates the exemplary structure with minimal construction detail. As shown, a vein 205 has a length **l**, measured between the centres of respective nodes 210 and 210', and a thickness **t**, measured at its mid-point between adjoining nodes 210 & 210'. The mid-point of a vein is typically the thinnest point along the vein. In addition, for the present purposes, a node 210' is said to have a diameter measurement **d** defined by the largest diameter circle that can fit within the glass that forms the node. Of course, nodes in other kinds of cladding structures may have significantly different form, in which case it would not be sensible to characterise those nodes in terms of a diameter. For the sake of construction only, a node is defined herein by three notional circular paths 215, each one being positioned between and abutting a different pair of neighbouring veins that join the node. The perimeter of the node is defined by the portions of the circular paths 215 which begin at a point p and end at a point q along first and second veins respectively. Points p and q are equidistant from the centre of the node 210'. It will be appreciated that the diameter, d, of the node 210' is a function of the thickness, t, of the veins, the distance of p from the centre of the node and the pitch Λ, or centre to centre distance between neighbouring cells, of the structure.

Referring again to Figure 1, there are twelve boundary cells 125, 135 and eighteen nodes 150 around the core defect boundary 145, which are referred to herein as "**boundary nodes**". Specifically, there is a boundary node 155 wherever a vein that joins two neighbouring boundary cells meets the core defect boundary 145. In Figure 1, these nodes 155, which are referred to herein as "**end boundary nodes**", have slightly smaller diameters than the nodes 160 within the cladding structure, which are referred to herein as "**cladding nodes**". Additionally, there is a boundary node 165 at the mid point of each relatively longer side of the core defect boundary 145. These boundary nodes 165, which are referred to herein as "**intermediate boundary nodes**", coincide with the mid-point along the inner-facing vein 140 of each pentagonal boundary cell 135. The intermediate boundary nodes result from a possible manufacturing process that is used to form the structure in Figure 1, as will be described in more detail below.

According to the examples provided herein, the veins 130 & 140 around the core defect boundary, known herein as "**boundary veins**" have similar thicknesses to the veins 115 within the cladding structure, known herein as "**cladding veins**". In general, each node of any kind has a diameter that is greater than the thickness of the veins that join that node. As will be described below, it is possible to control the diameters of particular nodes during manufacture of a fibre.

The structure in Figure 1, and each of the following examples of different structures, has the following common characteristics: a pitch $\Lambda$ of the cladding chosen between values of approximately $3\mu m$ and $6\mu m$ (this value may be chosen to position core-guided modes at an appropriate wavelength for a particular application); a thickness t of the veins of 0.0586 times the chosen pitch $\Lambda$ of the cladding structure (or simply $0.0586\Lambda$); an AFF of approximately 87.5%; and a ratio **R** having a value of 0.5. **R** is defined as the ratio of the distance of p' from the centre of the nearest node to half the length of a vein, **l/2**; where p' is a point along the centre-line of a vein and is defined by a construction line that passes through the centre-line, the centre of circle 215 and the point p, where the circle meets the vein. It will be apparent that the maximum practical value of R is 1, at which value the cladding holes are circular, and the minimum value is dictated by the thickness t and length l of the veins, at which value the diameter of the circle 215 tends to zero and the cladding holes are hexagonal. In practice, due to surface tension effects during the drawing of a PBG fibre, the value of R will tend to be greater than its theoretical minimum.

Given R, t and Λ, for practical purposes, the diameter d of the cladding nodes is found to be:

$$d = \frac{2R\Lambda}{\sqrt{3}} - \Lambda R + t \qquad \text{(Equation 1)}$$

According to the examples provided herein, the diameter of each end boundary node 155, $d_e$, is smaller than the diameter of the cladding nodes 160. Accordingly, it is assumed that the value of R is a minimum for the circular path 215, which is inside the core defect 110. In other words, for an end boundary node 155, there is no measurable circular path 215 inside the core defect 110 and the boundary veins 130, 140 meet at a substantially rectilinear, rather than rounded, intersection. The other two circular paths 215 for the end boundary node 155, which are inside two neighbouring boundary cells 125 & 135, have a value of R equal to 0.5.

The intermediate boundary nodes 165 are, in fact, oval shaped, having a major dimension which is 1/3 the length of the distance between the two node centres that lie on either side of the node. The minor dimension of the oval is 1/3 the size of the major dimension. Thus, the intermediate boundary nodes 165 have a diameter, according to the definition provided herein, that equals the minor dimension.

The present inventors have determined that it is possible to control the performance of PBG fibres in particular by aiming to maximise the amount of light that propagates in air within the fibre structure. This is in contrast to prior art teachings, which concentrate on maximising the amount of light that exists in a core region of a fibre structure. As has been described, it is desirable for a maximum amount of light to propagate in air in order to benefit from the properties of PBG fibres, such as reduced absorption, dispersion, non-linearity and, in addition, reduced mode coupling.

For the purposes of comparing aspects of the performance of various different structures it is useful to consider the modes that are supported in the band gap of various PBG fibre structures. This may be achieved by solving Maxwell's vector wave equation for the fibre structures, using known techniques. In brief, Maxwell's equations are recast in wave equation form and solved in a plane wave basis set using a variational scheme. An outline of the method may be found in Chapter 2 of the book "Photonic Crystals – Molding the Flow of Light", J.D. Joannopoulos et al., ©1995 Princeton University Press.

Figures 3 and 4 illustrate six exemplary PBG fibre structures that will be considered hereafter. Figure 3 illustrates three structures identified as S1, S2 and S3 herein, which are seven-cell core defect structures. S1 is the same as the structure illustrated in Figure 1 and is reproduced in Figure 3 for convenience. S2 and S3, while not being embodiments of the present invention per se, reinforce various characteristics of the invention, as determined by the present inventors, and, in particular, are discussed herein in order to illustrate how the mode spectrum of a given structure may vary significantly, compared with S1, without varying the size of the core defect.

Figure 4 illustrates three structures identified as S4, S5 and S6, which are exemplary embodiments of the present invention, each having a nineteen-cell core defect. S4, S5 and S6, apart from core defect size, have the same cladding characteristics as S1, S2 and S3. S1 to S3 have a maximum core defect radius of 1.5275Λ. In contrast, S4 to S6 have a maximum core defect radius of 2.5166Λ.

The characteristics of S1 have been described above and the characteristics of S2 to S6 will now be described:

S2 has reduced boundary node diameters compared with S1. More particularly, S2 has no apparent intermediate boundary nodes along the core defect boundary 345 and the diameters of the end boundary nodes 355 are significantly smaller than the cladding nodes 360. According to the definitions provided herein for convenience, the end boundary nodes 355 have a minimum possible diameter, with a value of R equal to its minimum, such that the cladding veins 315 meet the boundary veins 330, 340 at rectilinear rather than rounded angles. As such, the diameters of the end boundary nodes 355 are similar to the thickness of the boundary veins 330, 340. In contrast, as for S1, the cladding nodes 360 have diameters that are significantly larger than the thickness of their adjoining veins 315.

S3 has no apparent intermediate boundary nodes, as in S2, and the end boundary nodes 355 have a similar diameter to those in S1.

S4 has an additional ring of cladding cells removed compared with S1. This forms a core defect 410 equivalent to nineteen missing cladding cells. Similar to S1, S4 has boundary nodes 450 that are significantly larger in diameter than the respective boundary veins and there are hexagonal cells 425 at each corner of the core defect 410. However, in contrast to S1, which has one generally pentagonal cell along each side of the core defect boundary 145, S4 has two generally pentagonal cells 435 along each side of the core defect boundary 445. This leads to there being two intermediate boundary nodes 455 along each side of the core

defect boundary 445, roughly coincident with the mid-point of the vein 440 of each pentagonal cell 425 that borders the core defect boundary 445. There are also three end boundary nodes 455 per relatively longer side of the core defect boundary 445, compared with two 435 for the seven-cell core defect structures. Overall, S4 has eighteen cells sharing veins with the core defect boundary 445.

S5 is similar to S2 in the respect that it has reduced-diameter end boundary nodes 455', which do not have diameters that are significantly larger than the respective veins, and there are no apparent intermediate boundary nodes. All other parameters of S5 are the same as S4.

S6 has no apparent intermediate boundary nodes, as in S3, and the end boundary nodes 455 have a similar diameter to those in S1. All other parameters of S6 are the same as S4.

Figures 5 and 6 each show three mode spectra, identified as P1 to P3 and P4 to P6 respectively. Each spectrum P1 to P6 relates to a respective PBG fibre structure S1 to S6. The horizontal axis of each spectrum is normalised frequency, $\omega\Lambda/c$, where $\omega$ is the frequency of the light, $\Lambda$ is the pitch of the cladding structure, and c is the speed of light in a vacuum. The vertical axis of each spectrum relates to mode intensity for a given normalised wave-vector $\beta\Lambda=13$, against which the spectrum is plotted, where $\beta$ is the chosen propagation constant for the calculations. The spectra are produced using a Finite-difference Time Domain (FDTD) algorithm, which computes the time-dependent response of a given hollow core structure to a given input. This technique has been extensively used in the field of computational electrodynamics, and is described in detail in the book "Computational Electrodynamics: The Finite-Difference Time-Domain Method", A. Taflove & S.C. Hagness, ©2000 Artech House.

With reference to spectra P1 to P6, each vertical spike indicates the presence of at least one mode at a corresponding normalised frequency. In some cases, multiple modes may appear as a single spike or as a relatively thicker spike compared with other spikes in a spectrum. This is due to the fact that the input data used to generate the spectra was not of a high enough resolution to distinguish very close modes. As such, the mode spectra should be taken to provide only an approximation to the actual numbers of modes that exist for each structure, which is satisfactory for enabling a general comparison between spectra herein.

On each spectrum, a 'light line' for the respective structure is shown as a solid vertical line at $\omega\Lambda/c=13=\beta\Lambda$, and band edges, which bound a bandgap, are represented as two dotted

vertical lines, one on either side of the light line, with a lower band edge of the bandgap at around $\omega\Lambda/c=12.92$ and an upper band edge of the bandgap at around $\omega\Lambda/c=13.30$. A bandgap in P1 to P6 is a range of frequencies of light for a given $\beta$.

In theory, modes that fall outside of the bandgap are those which would also be supported in a cladding structure with no core defect. In such a structure, there would be no modes supported in the bandgap. The introduction of the core defect into a structure leads to modes being supported in the bandgap. In addition, as can be seen by comparing the different spectra, modes outside of the bandgap vary in their intensity and location as a result of the influence on the structure of the core defect. The band edges, however, are in the same position for each spectrum, and are not influenced by the presence of a core defect.

Modes that are between the light line and the lower band edge (that is, to the left of the light line) will concentrate in the glass and be evanescent in air whereas the modes that are between the light line and the upper band edge (that is, to the right of the light line) may be air-guiding.

As shown in P1, relating to S1, there are around three modes between the light line and the lower band edge and around nine modes between the light line and the upper band edge (taking the thicker spikes as two modes). It is clear that S1 supports a significant number of modes, some of which could be air-guiding; although, it is not necessarily the case that all of these modes will be excited by a given light input. Analysis of the individual modes shown in the bandgap of P1 leads to a finding that the mode marked as F1 is an air-guiding mode, which most closely resembles the form of a fundamental mode in a typical standard optical fibre and supports the maximum amount of light in air. The mode is found to be degenerate.

As shown in P2, relating to S2, approximately two modes lie between the light line and the lower band edge and there are around twelve modes between the light line and the upper band edge. As with S1, S2 supports a significant number of modes, some of which could be air-guiding. The mode marked F2 in P2 is found to be a degenerate, air-guiding mode that most closely resembles the form of a fundamental mode in a typical standard optical fibre and supports the maximum amount of light in air.

The structural characteristics of S2 are not that different from those of S1; the only difference being the reduced boundary node sizes in S2. Notably, the core defect diameters of the two structures are the same. However, the mode spectra for the two structures are

significantly different, there being more potentially-air-guiding modes supported by S2 but fewer modes that are evanescent in air.

As shown in P3, relating to S3, there are around three modes between the light line and the lower band edge and around thirteen modes between the light line and the upper band edge. Again, it is clear that S3 supports a significant number of modes, some of which could be air-guiding. The mode marked F3 in P3 is a degenerate, air-guiding mode that most closely resembles the form of a fundamental mode in a typical standard optical fibre and supports the maximum amount of light in air.

Again, the structural characteristics of S3 are only subtly different from those of either S1 or S2, with the core defect diameters of all structures being the same. However, the mode spectrum for S3 is, once more, significantly different from the mode spectra of either S1 or S2.

As shown in P4, relating to S4, which is a nineteen-cell core defect structure according to an embodiment of the present invention, there are approximately two to four modes between the light line and the lower band edge and in excess of twenty modes between the light line and the upper band edge of the bandgap region. Clearly, S4 appears to support significantly more modes than any of the foregoing seven-cell core defect structures. The mode marked F4 in P4 is again a degenerate, air-guiding mode that most closely resembles the form of a fundamental mode in a typical standard optical fibre and supports the maximum amount of light in air.

The core defect diameter of S4 is significantly larger than in S1, whereas the other parameters are substantially the same. On the basis of prior art thinking it is not a surprise that there appear to be significantly more modes supported in the nineteen-cell core defect structure of S4 compared with any of the seven-cell core defect structures S1 to S3.

As shown in P5, relating to S5, there are approximately four modes between the light line and the lower band edge and around fifteen to twenty modes between the light line and the upper band edge. Again, S5 appears to support significantly more modes than the foregoing seven-cell core defect structures. The mode marked F5 in P5 is a degenerate, air-guiding mode that most closely resembles the form of a fundamental mode in a typical standard optical fibre and supports the maximum amount of light in air.

The mode spectra for S4 and S5 are similar in terms of numbers of modes, with both structures supporting a number of evanescent and possibly air-guiding modes.

As shown in P6, relating to S6, there is a single mode between the light line and the lower band edge and approximately twelve to fifteen modes between the light line and the upper band edge. Thus, S6 appears to support significantly fewer modes than either of S4 or S5, even though the core defect sizes are the same. Surprisingly, the mode spectrum of S6 appears to resemble, in both numbers and positions of modes, the mode spectrum of S2, which is a seven-cell core defect structure. This is contrary to prior art thinking, which indicates that larger core defects should support, proportionately, more modes. The mode marked F6 in P6 is again a degenerate, air-guiding mode that most closely resembles the form of a fundamental mode in a typical standard optical fibre and supports the maximum amount of light in air.

On the basis of the above six examples of different PBG fibre structures, it is clear that the numbers and locations of modes in a mode spectrum are not determined only by size of the core defect, index difference between a core and cladding and wavelength of light; even when the cladding structure is fixed. Taking S1 to S3, for example, it is clear that the locations of modes and, in particular, the number of modes that are likely to be evanescent in air or possibly air-guiding, can be varied significantly by varying the node size about the core defect boundary, without the need to vary the core defect size. Additionally, while certain PBG fibre structures that support a greater number of modes – especially potentially air-guiding modes – may be made by increasing the core defect size for any given cladding structure, it also appears possible to increase the core defect size without significantly increasing the number of modes that are supported by the structure. This is surprising and contrary to the thinking in the prior art.

Figure 7 comprises six plots, D1 to D6, which show the mode intensity distributions, over a transverse cross-section of a respective PBG fibre structure, for modes F1 to F6 respectively. Each plot shows the position and orientation of x and y planes, which correspond to the x and y planes of the structures, as illustrated in Figures 3 and 4. These plots were produced using the results of solving Maxwell's equations for each structure, as described above.

The graphs in Figures 8 and 9 show the mode intensity for modes F1 to F6 along longitudinal planes x and y of D1 to D6 respectively. The intensity values are normalised so that the maximum intensity of the mode is at 0dB on the graph; the y-axis scale being logarithmic. The shaded vertical lines and bands across the graphs coincide with and represent the glass regions of the actual respective structure along the x and y planes. For the

x and y planes, therefore, it is possible to see how the light intensity of the mode varies in the air and glass, and across the glass/air boundaries, of each structure.

Table 1 below shows, for modes F1 to F6, the approximate normalised frequency of where the mode lies within the bandgap of its respective structure and the amount of light that is in air rather than in the high index silica regions.

| Mode Number | Normalised frequency ($\omega\Lambda/c$) | % light in air |
|---|---|---|
| F1 | 13.14 | 92.8 |
| F2 | 13.12 | 97 |
| F3 | 13.11 | 97.5 |
| F4 | 13.05 | 97.7 |
| F5 | 13.04 | 99.6 |
| F6 | 13.04 | 99.5 |

Table 1

The percentage of light in air for modes is found by calculating the integral of the light intensity across only the air regions of the plots in Figure 7 and normalising to the total power.

Plot D1 shows the mode intensity distribution for the F1 mode, which was found at a normalised frequency $\omega\Lambda/c$ of 13.1374. Plot D1 together with graphs x1 and y1 show that the F1 mode has a generally round central region in the core defect. The central region of the mode is intense at its centre and decays sharply towards the core defect boundary. There are two intense satellites to the left and right of the central region, coincident with the core defect boundary, and a number of less intense satellites that form a broken ring around the central region. As shown in graph x1, the satellites to the left and right of the central region have slightly higher intensities than the maximum intensity of the central region. It is significant to note that these intense satellites, along with the larger ones of the less intense satellites around the boundary, appear to coincide with the intermediate boundary nodes of S1. In addition, it would appear that the remainder of the less intense satellites appear to coincide with the end boundary nodes of S1. There is some visible evidence in D1 of some light being concentrated further out from the centre of the structure than the core defect boundary although, as is supported with reference to graphs x1 and y1, the light intensity drops-off rapidly away from the central region. The light that is further out appears to coincide with cladding nodes.

It is apparent that, for the seven-cell core defect structure S1, a significant amount of light concentrates in the pronounced intermediate boundary nodes. It is apparent, however, that the F1 mode is air-guiding, with a significant fraction of the light existing in the core defect and with a local intensity minimum of the mode falling within the core defect boundary. The intensity of the light in the glass of the cladding structure decreases significantly moving further away from the core defect boundary.

Plot D2 shows the mode intensity distribution of the F2 mode in the transverse plane of S2. The mode was found at a normalised frequency $\omega\Lambda/c$ of 13.1182. Plot D2 together with graphs x2 and y2 show that the F2 mode has a generally round central region in the core defect. The central region is intense at its centre and decays sharply towards the core defect boundary. There are six relatively lower intensity satellites about the central region, coincident with the core defect boundary, and visible evidence of lower intensity satellites in glass further out from the central region. The six satellites around the core defect boundary have a lower intensity than the maximum intensity of the central region, in contrast to the intense satellites of plot D1. It is believed that in plot D2 the intensities of the satellites around the core defect boundary are less than in plot D1 due to the removal of the pronounced intermediate boundary nodes; in-keeping with the observation that, for a seven-cell core defect structure, light concentrates in the pronounced intermediate boundary nodes.

As with the F1 mode, it is apparent that the F2 mode is air-guiding. It is also apparent that some of the light concentrates in the glass of the cladding structure.

The percentage of light in air for the F2 mode is 97%. This value is significantly larger than the value of 92.8% for the F1 mode even though the core defect size is the same. This increase in the amount of light in air is attributed to the reduction in diameter of the boundary nodes. Accordingly, it is expected that S2 will have improved loss, dispersion, non-linearity and mode coupling characteristics compared with S1.

Plot D3 shows the mode intensity distribution of the F3 mode in the transverse plane of S3. The mode was found at a normalised frequency $\omega\Lambda/c$ of 13.1090. The qualitative and quantitative characteristics of the F3 mode, as shown in plot D3 and graphs x3 and y3, very closely match those of the F2 mode. Similarly, the value of the percentage of light in air for the F3 mode is 97.5%, which is very close to the figure for the F2 mode. Accordingly, it is expected that S3 will also have improved loss, dispersion, non-linearity and mode coupling characteristics compared with S1.

Plot D4 shows the mode intensity distribution of the F4 mode in the transverse plane of S4. The mode was found at a normalised frequency $\omega\Lambda/c$ of 13.0452. Plot D4 together with graphs x4 and y4 show that the F4 mode has a generally round central region in the core defect. The central region is intense at its centre and decays rapidly towards the core defect boundary, although not as rapidly as in Plots D1 to D3. The central region has a local minimum that falls close to and within the core defect boundary, which means that the central region in plot D4 has a diameter in the order of two pitches longer than for any of the seven-cell core defect structures.

There are a number of low intensity satellites around the central region in plot D4, which appear to coincide with the boundary nodes of S4. From graphs x4 and y4, these satellites appear to be more than 20dB lower than the peak intensity of the central region. However, it should be noted that the x4 plane does not cross the core defect boundary at an intermediate boundary node, whereas planes x1 to x3 do, which means it is not possible to make a direct comparison of satellite intensity between graph x4 and graphs x1 to x3. The fact that the satellites in plot D4 appear so faint, though, does indicate that they have a significantly reduced intensity compared with satellites in plots D1 to D3.

The F4 mode is apparently air-guiding, with a significant fraction of the light existing in the core defect. Light which is guided outside of the core defect is concentrated in the glass. The percentage of light in air for S4 is 97.7%. This value is an improvement over the highest seven-cell core defect structure value by a small margin (0.2%) and a significant improvement (4.9%) over S1, which has a similar boundary node configuration. Accordingly, it is expected that S4 will have improved loss, dispersion, non-linearity and mode coupling characteristics compared with S1.

Plot D5 shows the mode intensity distribution of the F5 mode in the transverse plane of S5. The mode was found at a normalised frequency $\omega\Lambda/c$ of 13.0435. Plot D5 together with graphs x5 and y5 show that the F5 mode is very similar in form to the F4 mode, with an intense central region and only very faint satellites visible outside of the central region. These satellites appear fainter than those in plot D4. Like the F4 mode, it is apparent that the F5 mode is air-guiding with a significant fraction of the light existing in the core defect.

The value of percentage of light in air for the F5 mode is 99.6%, which is significantly higher than the value of 97.7% for the F4 mode, even though the core defect sizes are the same. This increase in light in air value is attributed to the reduction in size of the boundary

nodes in S5 when compared with S4. Again, it is expected that S5 will have significantly improved loss, dispersion, non-linearity and mode coupling characteristics compared with S1.

Plot D6 shows the mode intensity distribution of the F6 mode in the transverse plane of S6. The mode was found at a normalised frequency $\omega\Lambda/c$ of 13.0423. Plot D6 together with graphs x6 and y6, relating to the F6 mode, very closely match the qualitative and quantitative characteristics of the F5 mode. In addition, the value of the percentage of light in air for the F6 mode is 99.5%, which is similar to the value for the F5 mode. Accordingly, like S5, it is expected that S6 will have significantly improved loss, dispersion, non-linearity and mode coupling characteristics compared with S1, while at the same time not supporting a significantly increased number of modes compared with the seven-cell core defect structures of Structures S1 to S3.

With reference to Figure 10, prior art structures of the kind exemplified by S1 may be made from a perform 1000 comprising a stack of hexagonal capillaries 1005. The hexagonal capillaries 1005 each have a circular bore. The cladding nodes 160 and end boundary nodes 155 (from Figure 1) of the PBG fibre structure result from the significant volume of glass that is present in the perform 1000 wherever the corners 1010, 1015 of neighbouring capillaries meet. The intermediate boundary nodes 165 are formed from glass at the inwardly-facing corners 1020 of the capillaries that bound an inner region 1025 of the preform 1000, which is to become the core defect region 110 of a PBG fibre structure. These corners 1020, and the two sides of each capillary that meet at the corners, recede due to surface tension as the stack of capillaries is heated and drawn. Such recession turns the two sides and the corner 1020 into a boundary vein 140, with an intermediate boundary node 165. The inner region 1025 may be formed by omitting the inner seven capillaries from the preform and, for example, supporting the outer capillaries using truncated capillaries at either end of the stack as described in PCT/GB00/01249 (described above) or by etching away glass from inner capillaries in accordance with either PCT/GB00/01249 or US 6,444,133 mentioned above.

While it is possible to adapt the prior art processes in order to make the nineteen-cell core defect S4, which has intermediate boundary nodes, the present inventors have appreciated that it would be more difficult to manufacture either of S5 or S6 using the prior art techniques. In particular, it would be difficult to control the diameters of boundary nodes using hexagonal cross section capillaries of the kind described with reference to Figure 10. On the other hand, it is difficult to make structures having cladding nodes with diameters

which are significantly larger than their respective veins by using purely round capillaries, especially when the required AFF is high, for example higher than 80%.

Figure 11 illustrates one way of arranging a stack of capillaries 1100 to be drawn into a pre-form and fibre of the kind that is exemplified by S6. S6 has no apparent intermediate boundary nodes and the end boundary nodes 155 are smaller in diameter than the cladding nodes 160. The cladding is formed by stacking round cross section capillaries 1105 in a close-packed, triangular lattice arrangement. The cladding capillaries 1105 have an outer diameter of 1.04mm and a wall thickness of 40μm. The inner region 1110 of the stack contains a large diameter capillary 1115 having an outer diameter of 4.46mm and a wall thickness of 40μm. The large diameter capillary 1115 supports the cladding capillaries while the stack is being formed and eventually becomes part of the material that forms a core defect boundary 145.

Interstitial voids 1120 that form at the locus of each close-packed, triangular group of three cladding capillaries are each packed with a glass rod 1125, which has an outer diameter of 0.498mm. The rods 1125 are inserted into the voids 1120 after the capillaries have been stacked. The voids 1120 that are packed with rods 1125 eventually form cladding nodes 160, which have a diameter that is significantly greater than the thickness of the veins that meet at the nodes 160. Omission of a rod from a void in the cladding would lead to the formation of a cladding node that has a significantly smaller diameter.

In order to avoid the formation of pronounced end boundary nodes 155, which have a diameter that is significantly greater than the thickness of the respective nodes, the voids 1130 that are formed between the cladding capillaries 1105 and the large diameter capillary 1115 are not packed with rods, thereby minimising the volume of glass that is available, during drawing of the stack 1100, for formation of the end boundary nodes 155. By design, the arrangement of capillaries and rods shown in Figure 11 does not lead to formation of intermediate boundary nodes.

The stack 1100 is arranged as described with reference to Figure 11 and is then over-clad with a further, relatively thick walled capillary (not shown), which is large enough to contain the stack and, at the same time, small enough to hold the capillaries and rods in place. The entire over-clad stack is then heated and drawn into a pre-form, during which time all the interstitial voids at the boundary, and remaining voids between the glass rods and the cladding capillaries, collapse due to surface tension. The pre-form is, again, over-clad with a final, thick silica cladding and is heated and drawn into optical fibre in a known way. If surface

tension alone is insufficient to collapse the interstitial voids, a vacuum may be applied to the interstitial voids of the pre-form, for example according to the process described in WO 00/49436 (The University of Bath).

The diameters of the end boundary nodes of a PBG fibre that would result from the stack in Figure 11 may be further reduced by using a large diameter capillary having a thinner wall. A limiting factor in reducing the wall thickness would be the ability to make such a capillary.

An alternative way to reduce the size of end boundary nodes 155 is by omitting a large diameter capillary altogether. As illustrated in Figure 12, the stack 1200 of cladding capillaries 1205 and rods 1225 is supported around an insert 1215, for example made from graphite, platinum, tungsten or a ceramic material, which has a higher melting point than silica glass and, preferably, a higher coefficient of thermal expansion. The stack 1200, including the insert 1215, is heated to allow the capillaries 1205 and rods 1225 to fuse into a preform. The preform is then allowed to cool and the insert 1215 is removed. It will be apparent that, at this point, the core defect would take on the hexagonal shape of the insert. An advantage of using an insert material having a higher coefficient of thermal expansion than silica is that, when the preform and insert 1215 are heated, the insert expands and increases the area of the central region 1210. When permitted to cool down again, the insert 1215 shrinks back down to its original size and the silica solidifies leaving an inner region that is larger than the insert. The insert, which as a result is loose-fitting in the central region, may then be removed readily from the preform with reduced risk of damaging or contaminating the preform. The resulting preform is then heated and drawn in the usual way to form a PBG fibre. During the drawing step, it will be appreciated that the corners of the hexagonal core defect will, by virtue of surface tension, retract and flatten off, leaving a twelve-sided core defect of the kind illustrated in structure S5.

On the basis of the foregoing discussion, it will be apparent to the skilled person that the use of an insert in the formation of a preform is not limited to formation of nineteen-cell core defect structures and could be applied to making preforms for other core defect sizes, for example one-cell, seven-cell or thirty-seven cell core defect structures. Indeed, all of these structures have a core defect notionally centred on a primitive unit cell. Of course, a structure could be made which has a core defect centred on a notional node, which lies at the centre of three notional neighbouring primitive unit cells. For example, the core defect could be made by removing three primitive unit cells that are arranged in a regular triangle, or three primitive

unit cells as well as the nine primitive unit cells around the three primitive unit cells, etc. Further, inserts having, for example, star-shaped, elongate, round, square, rectangular, elliptical or irregular cross sections, or any other practical shape for that matter, could be applied to making preforms for fibre structures.

A further alternative way to reduce the size of end boundary nodes 155 is by using the process described in PCT/GB00/01249 (described above), wherein the inner capillaries are replaced by truncated capillaries, which support the outer capillaries at either end of the stack. The stack may be drawn to an optical fibre in the normal way, and the parts of the fibre incorporating the truncated capillary material may be discarded. In principle, truncated capillaries may also be used to support the stack part way along its length.

The skilled person will appreciate that the various structures described above may be manufactured using a manufacturing process described with reference to Figures 11 or 12 or one of the prior art processes. For example, rather than using a stacking and drawing approach to manufacture, a preform may be made using a known extrusion process and then that preform may be drawn into an optical fibre in the normal way.

In addition, the skilled person will appreciate that while the examples provided above relate exclusively to PBG fibre cladding structures comprising triangular lattices, the present invention is in no way limited to such cladding structures. For example, the invention could relate equally to square lattice structures, or structures that are not close-packed.

CLAIMS

1. A photonic bandgap optical waveguide comprising:

a photonic bandgap structure, having a plane cross section and a length dimension that extends perpendicular to the plane cross section, the photonic bandgap structure, in the plane cross section, comprising a substantially periodic array of relatively low refractive index regions, being separated from one another by relatively high refractive index regions, which extend along the photonic bandgap structure in the length dimension, the array having a characteristic primitive unit cell and a pitch; and

a core defect, surrounded by the photonic bandgap structure, the core defect comprising a region of relatively low refractive index having a plane cross section and a length dimension that extends perpendicular to the plane cross section, said plane cross section and length dimension being parallel to the same dimensions of the photonic bandgap structure, the core defect having an area which is greater than sixteen times the area of a primitive unit cell.

2. The waveguide according to claim 1, wherein, in the plane cross section, the core defect comprises an area that is large enough to contain at least sixteen whole primitive unit cells.

3. The waveguide according to claim 1 or claim 2, wherein, in the plane cross section, the core defect comprises an area that is substantially equal to nineteen times the area of a primitive unit cell.

4. The waveguide according to claim 1 or claim 2, wherein, in the plane cross section, the core defect comprises an area that is large enough to contain at least nineteen whole primitive unit cells.

5. The waveguide according to any one of the preceding claims, wherein, in the plane cross section, the core defect region has at least two-fold rotational symmetry.

6. The waveguide according to any one of the preceding claims, wherein, in the plane cross section, the relatively low refractive index regions are arranged in a substantially triangular array in the photonic bandgap structure.

7. The waveguide according to any one of the preceding claims, wherein the primitive unit cell is centred on a single relatively low refractive index region, that being the largest relatively low refractive index region in the primitive unit cell.

8. The waveguide according to any one of the preceding claims, wherein, in the plane cross section, the core defect comprises an area substantially equal to the area of a first primitive unit cell, a first group of all primitive unit cells that surround the first primitive unit cell and a second group of all primitive unit cells that surround said first group of primitive unit cells.

9. The waveguide according to any one of the preceding claims, wherein, in the plane cross section, the core defect resulted from omission or removal of relatively high refractive index regions from a first primitive unit cell, a first group of all primitive unit cells that surrounded the first primitive unit cell and a second group of all primitive unit cells that surrounded said first group of primitive unit cells.

10. A photonic bandgap optical waveguide comprising:

a photonic bandgap structure, having a plane cross section and a length dimension that extends perpendicular to the plane cross section, the photonic bandgap structure, in the plane cross section, comprising a substantially periodic array of relatively low refractive index regions, being separated from one another by relatively high refractive index regions, which extend along the photonic bandgap structure in the length dimension, the array having a characteristic primitive unit cell and a pitch, the primitive unit cell being centred on a single relatively low refractive index region, that being the largest relatively low refractive index region in the primitive unit cell; and

a core defect, surrounded by the photonic bandgap structure, the core defect comprising a region of relatively low refractive index having a plane cross section and a length dimension that extends perpendicular to the plane cross section, said plane cross section and length dimension being parallel to the same dimensions of the photonic bandgap structure, wherein the core defect resulted from omission or removal of relatively high refractive index regions from a first primitive unit cell, a first group of all primitive unit cells that surrounded the first primitive unit cell and a second group of all primitive unit cells that surround said first group of primitive unit cells.

11. The waveguide according to claim 10, wherein the photonic bandgap structure comprises a substantially periodic, triangular array of relatively low refractive index regions.

12. The waveguide according to claim 11, wherein the core defect results from omission or removal of relatively high refractive index regions from a first primitive unit cell, the six primitive unit cells that surround the first primitive unit cell and the twelve primitive unit cells that surround said six primitive unit cells.

13. The waveguide according to any one of the preceding claims, wherein, in the plane cross section, the relatively low refractive index regions are separated from one another by relatively high refractive index veins that are joined at nodes.

14. The waveguide according to claim 13, wherein, in the plane cross section, at least some of the nodes within the photonic bandgap structure have diameters that are significantly larger than the thickness of the veins that meet at the nodes.

15. The waveguide according to claim 14, wherein, in the plane cross section, substantially all of the nodes within the photonic bandgap structure have diameters that are significantly larger than the thickness of the veins that meet at the nodes.

16. The waveguide according to any one of claims 13 to 15, further comprising, in the plane cross section, a boundary at the interface between the core defect and the photonic bandgap structure, the boundary comprising a plurality of relatively high refractive index veins that are joined at nodes.

17. The waveguide according to claim 16, wherein, in the plane cross section, the fraction of nodes which have diameters that are significantly larger than the thickness of the veins that meet at the nodes is less on the boundary than in a similar region of the photonic bandgap structure.

18. The waveguide according to any one of claims 15, to 17, wherein, in the plane cross section, the boundary includes substantially no nodes which have diameters that are significantly larger than the thickness of the veins that meet at the nodes.

19. The waveguide according to any one of claims 14 to 18, wherein, in the plane cross section, said nodes that are significantly larger than the thickness of the veins that meet at the nodes have a diameter that is at least 1.5 times the thickness of the veins.

20. The waveguide according to any one of claims 14 to 19, wherein, in the plane cross section, said nodes that are significantly larger than the thickness of the veins that meet at the nodes have a diameter that is at least 2 times the thickness of the veins.

21. The waveguide according to any one of the preceding claims, wherein at least some of the relatively low refractive index regions are voids filled with air or under vacuum.

22. The waveguide according to any one of the preceding claims, wherein at least some of the relatively high refractive index regions comprise silica glass.

23. The waveguide according to any one of the preceding claims, having an air-filling-fraction that is greater than 80%.

24. The waveguide according to any one of the preceding claims, having an air-filling-fraction that is greater than 85%.

25. The waveguide according to any one of the preceding claims, having an air-filling-fraction that is around 87.5%.

26. The waveguide according to any one of the preceding claims, which supports a mode in which greater than 98% of the mode power in the waveguide is in relatively low refractive index regions.

27. The waveguide according to any one of the preceding claims, which supports a mode in which greater than 99% of the mode power in the waveguide is in relatively low refractive index regions.

28. The waveguide according to any one of the preceding claims, which supports a mode in which greater than 99.5% of the mode power in the waveguide is in relatively low refractive index regions.

29. The waveguide according to any one of the preceding claims, which supports a mode having a mode profile that closely resembles the fundamental mode of a standard, single mode optical fibre.

30. The waveguide according to claim 29, wherein said mode supports a maximum amount of the mode power in relatively low refractive index regions compared with other modes that are supported by the waveguide.

31. An optical fibre comprising a waveguide according to any one of the preceding claims.

32. A transmission line for carrying data between a transmitter and a receiver, the transmission line including along at least part of its length a fibre according to claim 31.

33. A preform for making a photonic bandgap optical waveguide, the preform comprising:

a first part for forming a photonic bandgap structure of the photonic bandgap optical waveguide, the first part having a plane cross section and a length dimension that extends perpendicular to the plane cross section and, in the plane cross section, a substantially periodic array of relatively low refractive index regions, being separated from one another by relatively high refractive index regions, which extend along the first part in the length dimension, the array having a characteristic primitive unit cell and a pitch; and

a relatively low-index region which becomes a core defect in the photonic bandgap structure of the photonic bandgap optical waveguide, the relatively low index region being surrounded by said first part and having a plane cross section and a length dimension that extends perpendicular to the plane cross section, said plane cross section and length

dimension being parallel to the same dimensions of said first part, the relatively low index region having an area which is greater than sixteen times the area of a primitive unit cell.

34. A preform for making a photonic bandgap optical waveguide, the preform comprising:

a first part for forming a photonic bandgap structure of the photonic bandgap optical waveguide, the first part having a plane cross section and a length dimension that extends perpendicular to the plane cross section and, in the plane cross section, a substantially periodic array of relatively low refractive index regions, being separated from one another by relatively high refractive index regions, which extend along the first part in the length dimension, the array having a characteristic primitive unit cell and a pitch, the primitive unit cell being centred on a single relatively low refractive index region and encompassing no more than one relatively low refractive index region; and

a relatively low-index region which becomes a core defect in the photonic bandgap structure of the photonic bandgap optical waveguide, the relatively low index region being surrounded by said first part and having a plane cross section and a length dimension that extends perpendicular to the plane cross section, said plane cross section and length dimension being parallel to the same dimensions of said first part, the core defect resulting from omission or removal of relatively high refractive index regions from a first primitive unit cell, a first group of all primitive unit cells that surround the first primitive unit cell and a second group of primitive unit cells that surround said first group of primitive unit cells.

35. The preform according to claim 33 or claim 34, wherein the photonic bandgap structure comprises a substantially periodic, triangular array of relatively low refractive index regions.

36. The preform according to claim 35, wherein the core defect results from omission or removal of relatively high refractive index regions from a first primitive unit cell, the six primitive unit cells that surround the first primitive unit cell and the twelve primitive unit cells that surround said six primitive unit cells.

37. The preform according to any one of claims 33 to 36, wherein the first part comprises a stack of elongate members.

38. The preform according to claim 37, wherein at least some of the elongate members comprise, in the plane cross section, a relatively low refractive index inner region and a relatively high refractive index outer region, which surrounds the inner region.

39. The preform according to claim 38, wherein the at least some elongate members comprise capillaries.

40. The preform according to any one of claims 37 to 39, wherein at least some of the elongate members comprise solid rods.

41. The preform according to any one of claims 33 to 36, wherein the first part comprises a single, substantially rigid structure.

42. The preform according to claim 41, wherein the preform is formed by a process comprising extrusion.

43. A method of forming a photonic bandgap optical waveguide comprising the steps of forming the preform as claimed in any one of claims 33 to 42 and heating and drawing the preform into a photonic bandgap optical waveguide.

44. A method of forming a photonic bandgap optical waveguide comprising the steps:

forming a preform stack by stacking a plurality of elongate elements into a periodic array of elements, the elongate elements comprising a relatively low refractive index elongate inner region enclosed by a relatively high refractive index outer region;

omitting, or substantially removing from an inner region of the stack, a first element, a first number comprising all elements from around said first element and a second number comprising all elements from around said first number of elements; and

heating and drawing the stack, in one or more steps, into a photonic bandgap optical waveguide, characterised by a photonic bandgap structure that surrounds a core defect, the photonic bandgap structure having a plane cross section and a length dimension that extends perpendicular to the plane cross section and comprising, in the plane cross section, a periodic, triangular array of relatively low refractive index regions, being separated from one another

by relatively high refractive index regions, which extend along the photonic bandgap structure in the length dimension.

45. The method according to claim 44, wherein the preform stack comprises a substantially periodic, triangular array of elongate elements.

46. The method according to claim 45, wherein the inner region of the stack is formed by omission or substantial removal of a first element, the six elements that surround the first elements and the twelve elements that surround said six elements.

47. The method according to any one of claims 44 to 46, wherein the elements have a generally hexagonal transverse cross section

48. The method according to any one of claims 44 to 46, wherein the elements have a generally circular transverse cross section.

49. The method according to claim 48, wherein, when the elements are being stacked, first elongate interstitial voids are formed between elements.

50. The method according to claim 49, including the additional step of introducing elongate elements into at least some of the first interstitial voids.

51. The method according to claim 50, wherein at least some of the elongate elements comprise rods.

52. The method according to claim 50, wherein at least some of the elongate elements comprise capillaries.

53. The method according to any one of claims 50 to 52, wherein elongate elements are introduced into substantially all of the first interstitial voids.

54. The method according to any one of claims 44 to 53, including the additional step of introducing a further elongate element into the inner region to support the elements around the inner region.

55. The method according to claim 54, wherein second interstitial voids are formed between the elements around the inner region and the further elongate element.

56. The method according to claim 55, including the additional step of introducing elongate elements into at least some of the second interstitial voids.

57. The method according to claim 56, wherein at least some of the elongate elements comprise rods.

58. The method according to claim 56, wherein at least some of the elongate elements comprise capillaries.

59. The method according to any one of claims 56 to 58, wherein a reduced fraction of the rods are introduced into the second interstitial voids compared with the number of rods that are introduced into a similar configuration of first interstitial voids.

60. A method according to claim 55, wherein no elongate elements are introduced into the second interstitial voids.

61. A method according to any one of claims 56 to 59, wherein at least some of the elongate elements that are introduced into the second interstitial voids have a smaller cross sectional area than the elongate elements that are introduced into the first interstitial voids.

62. The method according to any one of claims 54 to 61, wherein the further elongate element has a relatively low refractive index elongate inner region enclosed by a relatively high refractive index outer region, which becomes part of the photonic bandgap optical waveguide.

63. The method according to any one of claims 54 to 61, wherein the further elongate element comprises a material that has higher melting point and coefficient of thermal expansion than the relatively high refractive index material in the elongate elements.

64. The method according to claim 63, further comprising the steps of:

heating the preform stack in order to fuse the elongate elements around the further elongate element;

cooling the preform stack; and

removing the further elongate element from the preform stack prior to heating and drawing the preform stack.

65. The method according to any one of claims 44 to 64, wherein at least some of the relatively low refractive index regions comprise air or are under vacuum.

66. The method according to any one of claims 44 to 65, wherein at least some of the relatively high refractive index regions comprise silica glass.

67. An optical fibre comprising a photonic bandgap optical waveguide made by the method of any one of claims 44 to 66.

68. A photonic bandgap optical waveguide comprising:

a photonic bandgap structure, having a plane cross section and a length dimension that extends perpendicular to the plane cross section, the photonic bandgap structure, in the plane cross section, comprising relatively low refractive index regions, being separated from one another by relatively high refractive index regions, which extend along the photonic bandgap structure in the length dimension; and

a core defect, surrounded by the photonic bandgap structure, the core defect comprising a region of relatively low refractive index having a plane cross section and a length dimension that extends perpendicular to the plane cross section, said plane cross section and length dimension being parallel to the same dimensions of the photonic bandgap structure,

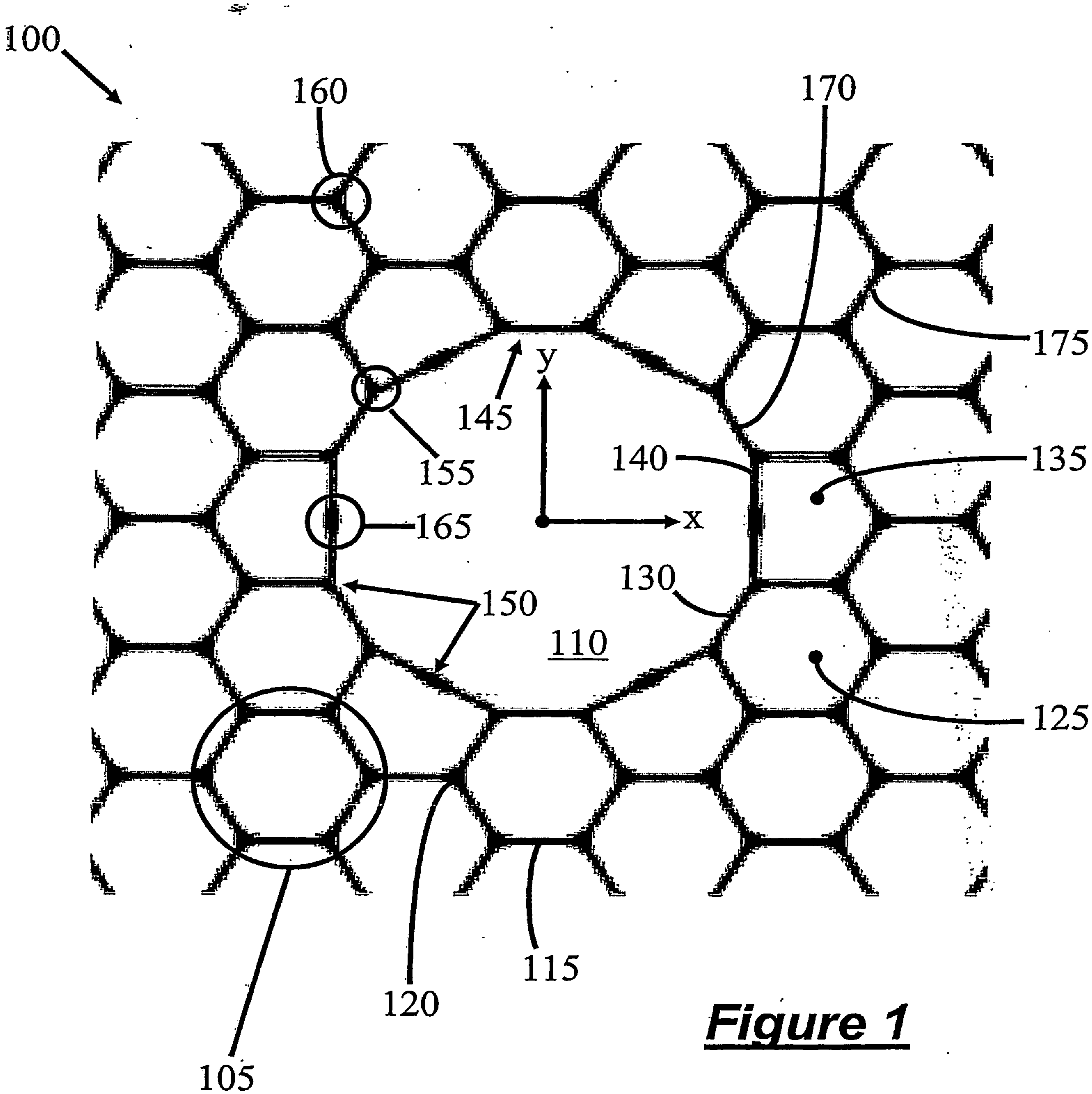
wherein, the waveguide supports a mode in which greater than 98% of the mode power in the waveguide is in relatively low refractive index regions.

69. A photonic bandgap optical waveguide comprising:

a photonic bandgap structure, having a plane cross section and a length dimension that extends perpendicular to the plane cross section, the photonic bandgap structure, in the plane cross section, comprising a substantially periodic array of relatively low refractive index regions, being separated from one another by relatively high refractive index regions, which extend along the photonic bandgap structure in the length dimension, the array having a characteristic primitive unit cell and a pitch; and

a core defect, surrounded by the photonic bandgap structure, the core defect comprising a region of relatively low refractive index having a plane cross section and a length dimension that extends perpendicular to the plane cross section, said plane cross section and length dimension being parallel to the same dimensions of the photonic bandgap structure,

wherein the core defect has an area which is greater than thirteen whole primitive unit cells.


100
160
170
175
145
y
155
140
135
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x
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150
110
125
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115
105

Figure 1

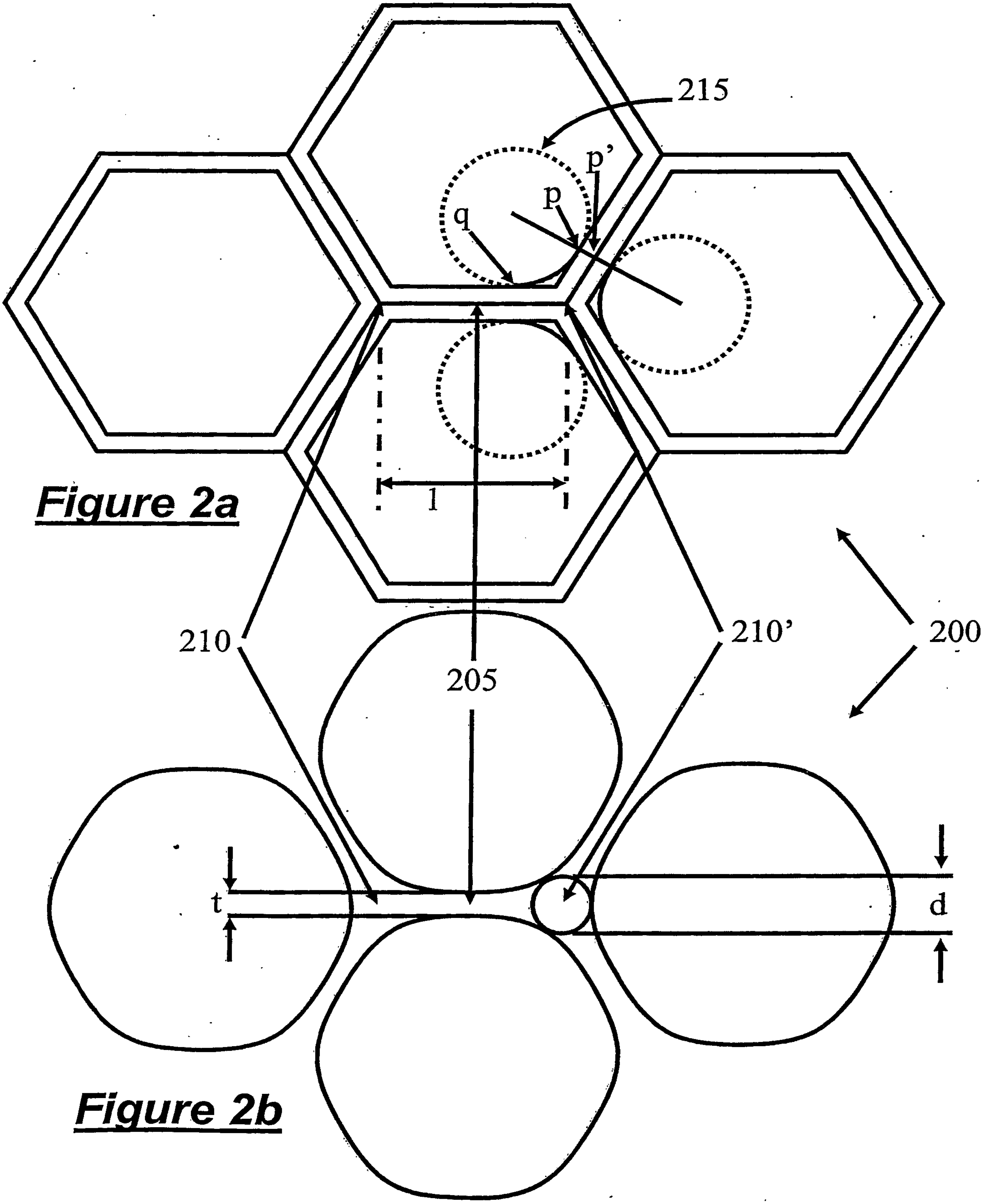


**Figure 2a**

**Figure 2b**

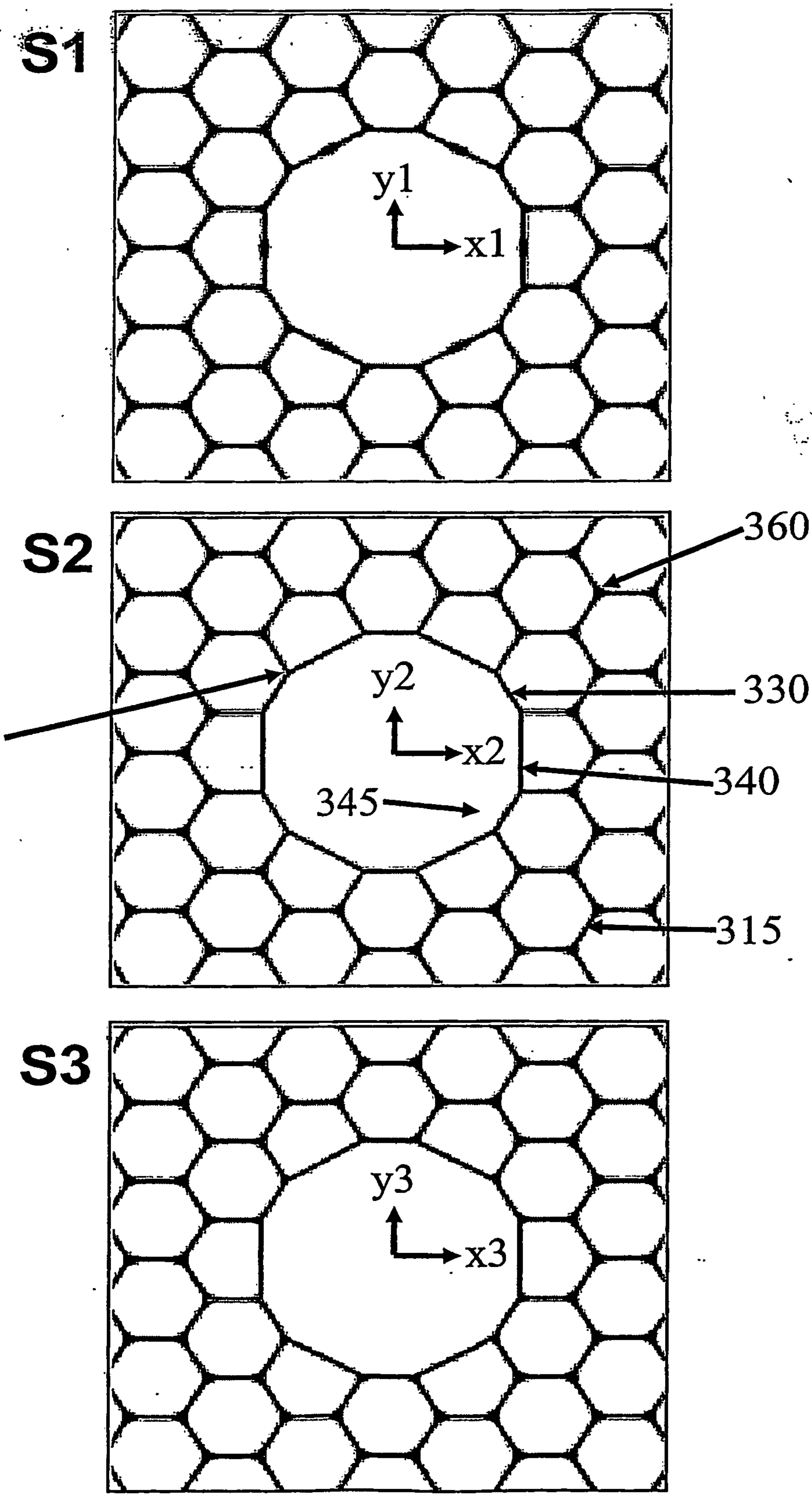


Figure 3

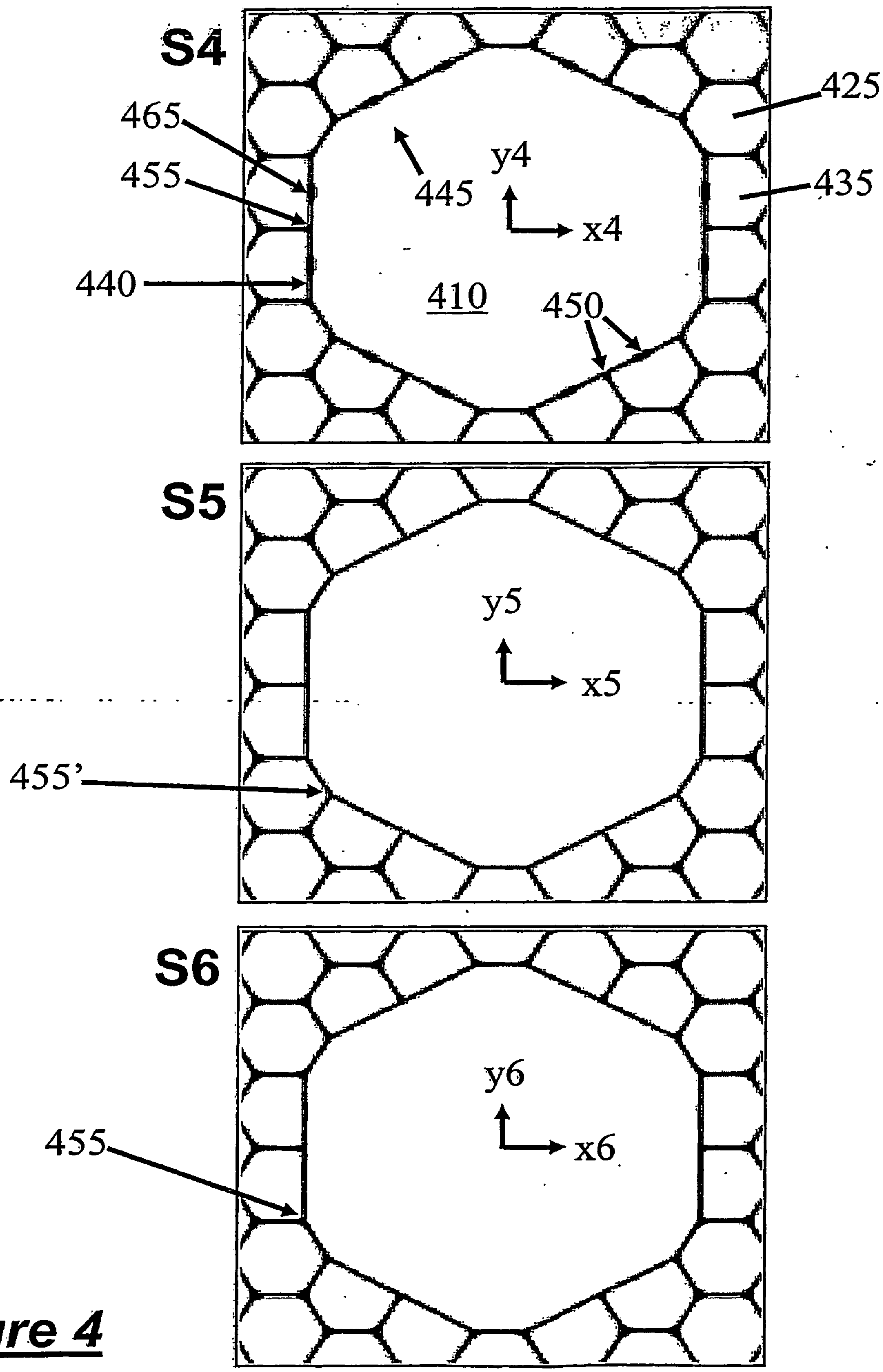


Figure 4

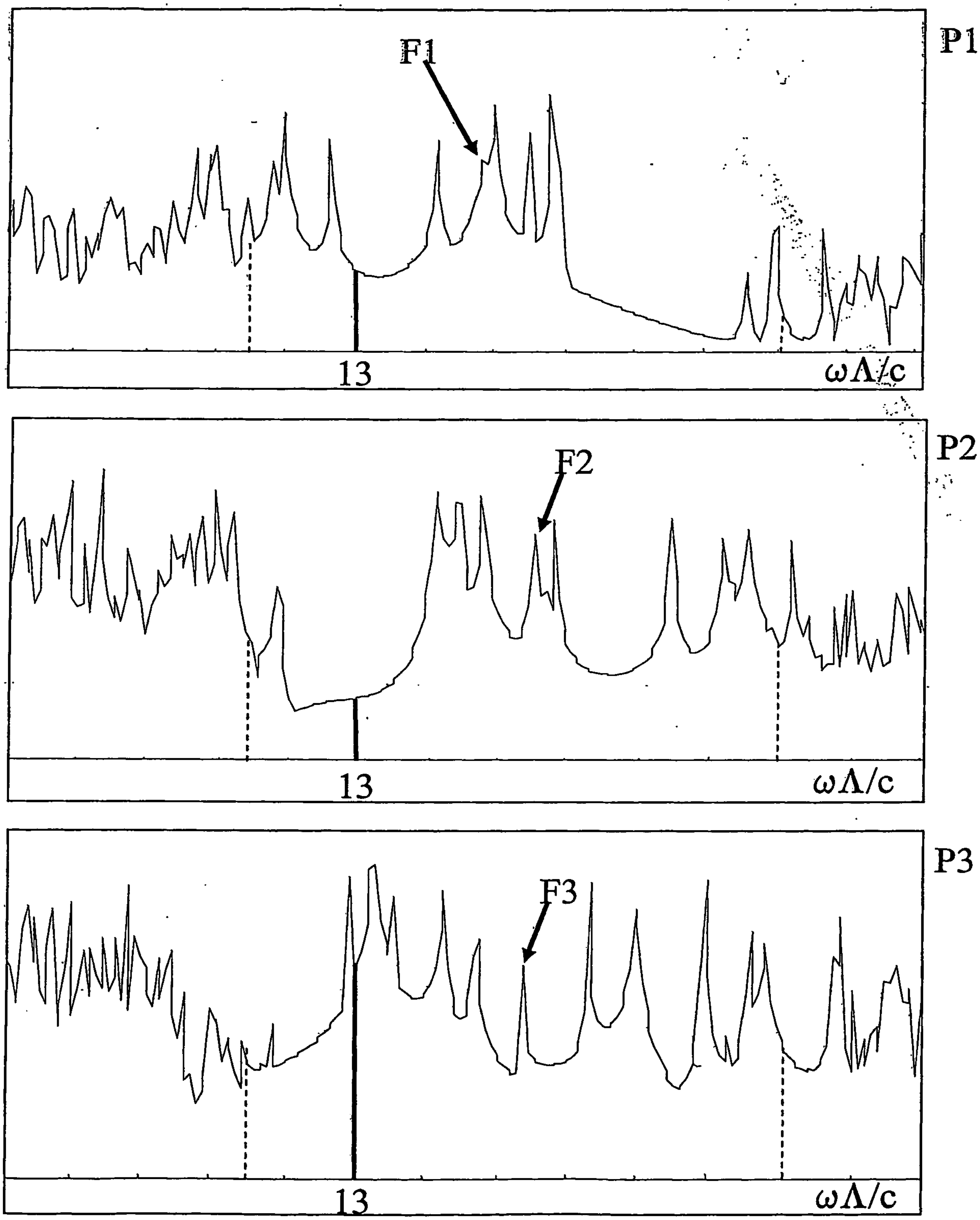


***Figure 5***

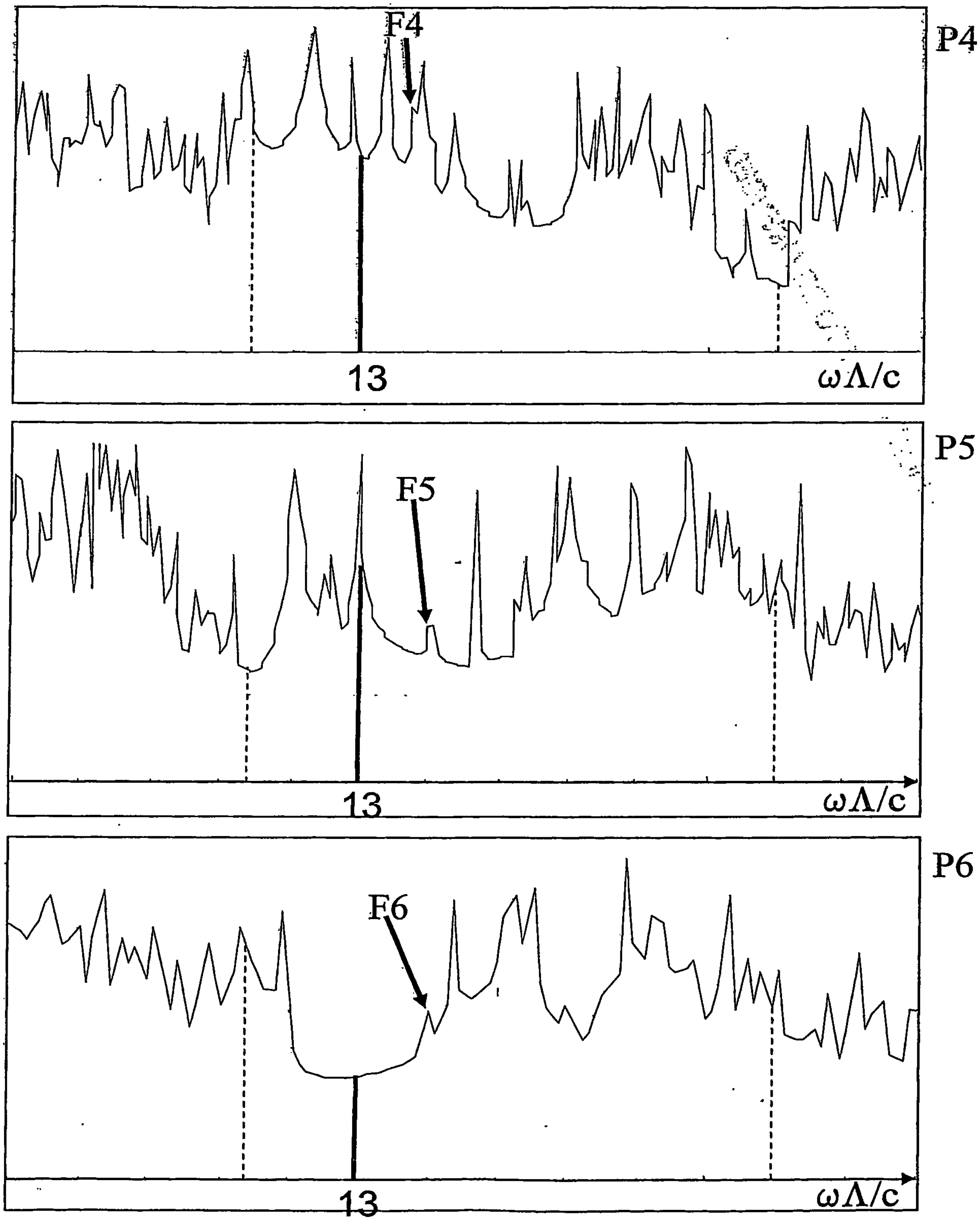


Figure 6

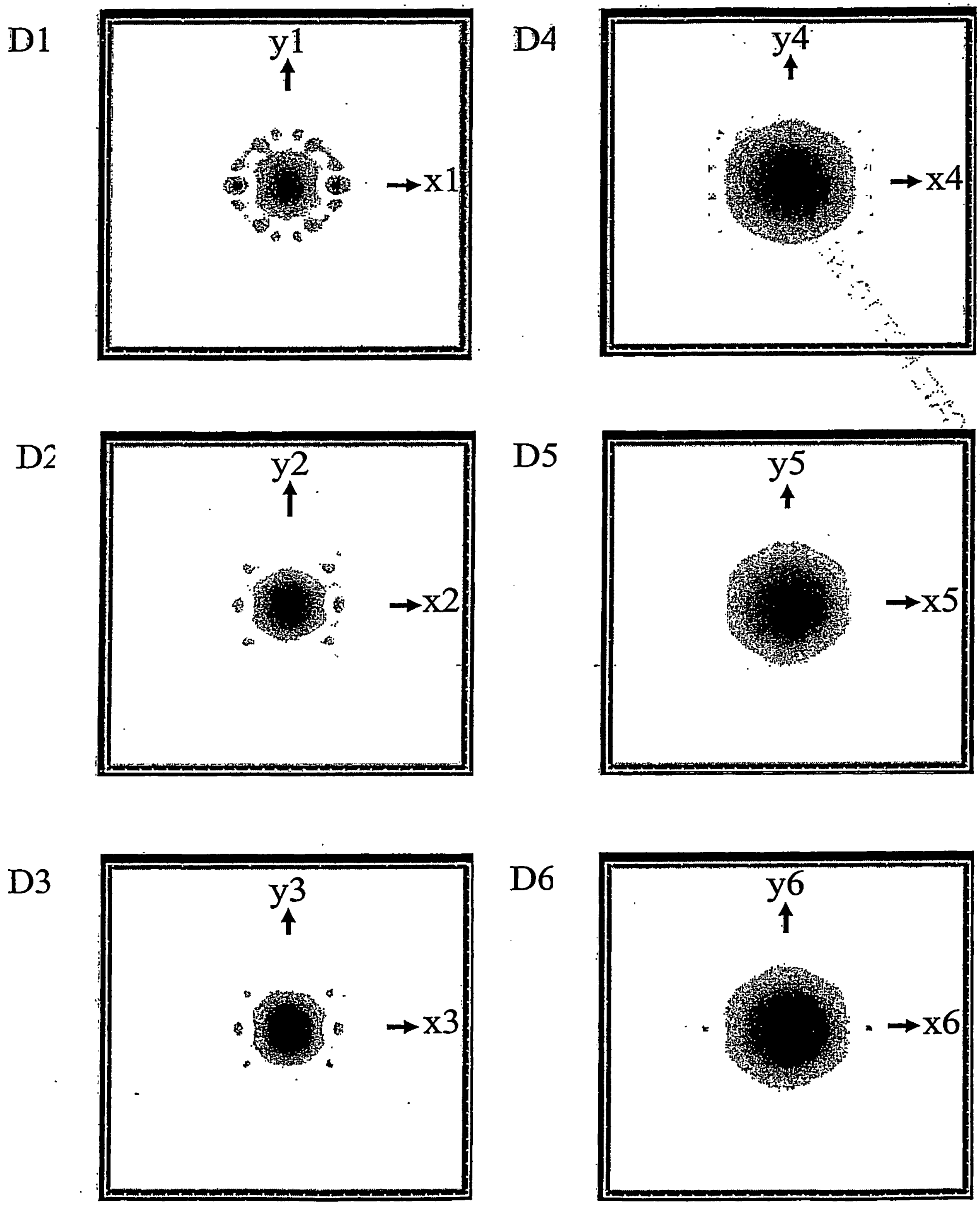


*Figure 7*

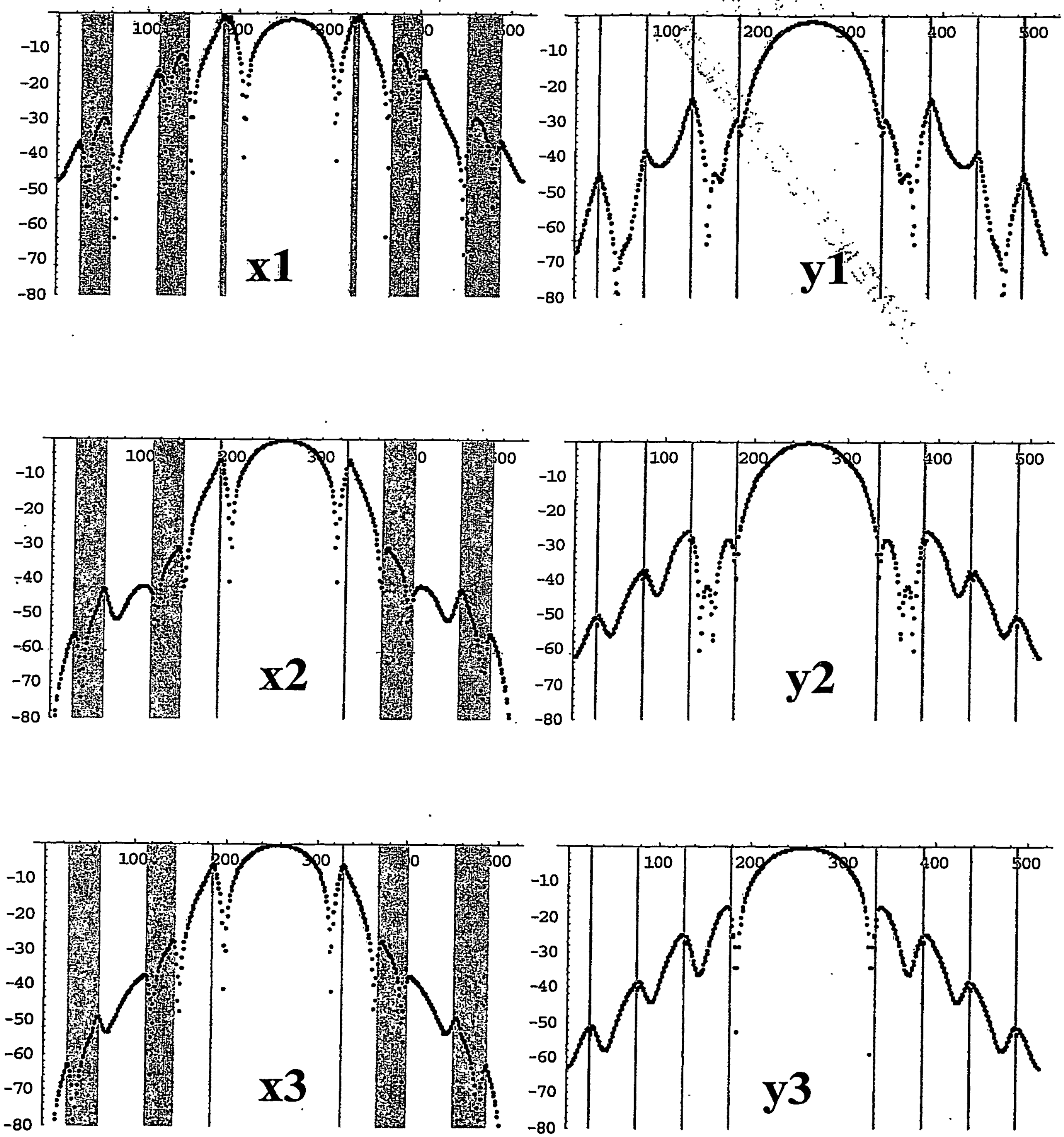


*Figure 8*

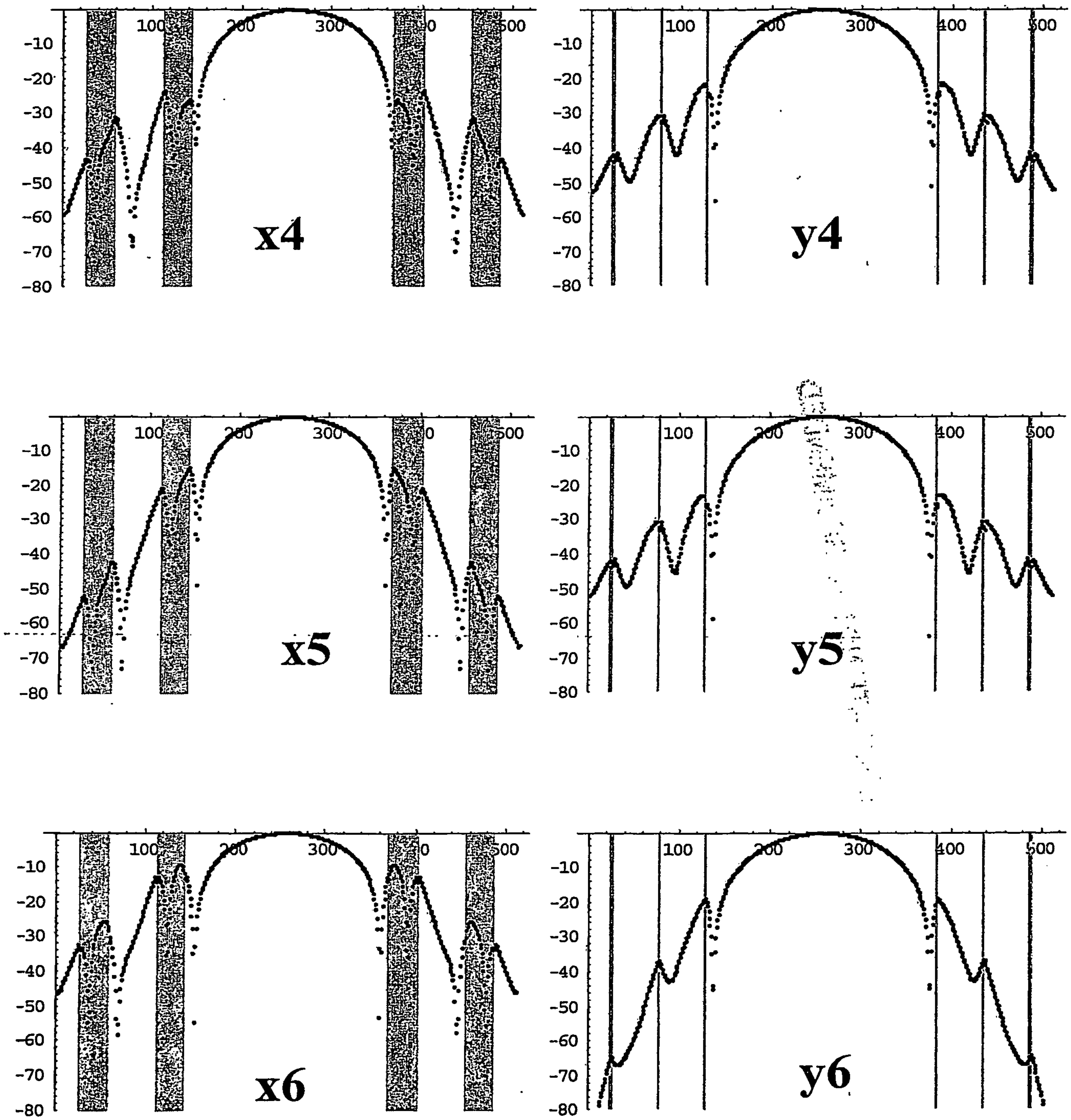


Figure 9

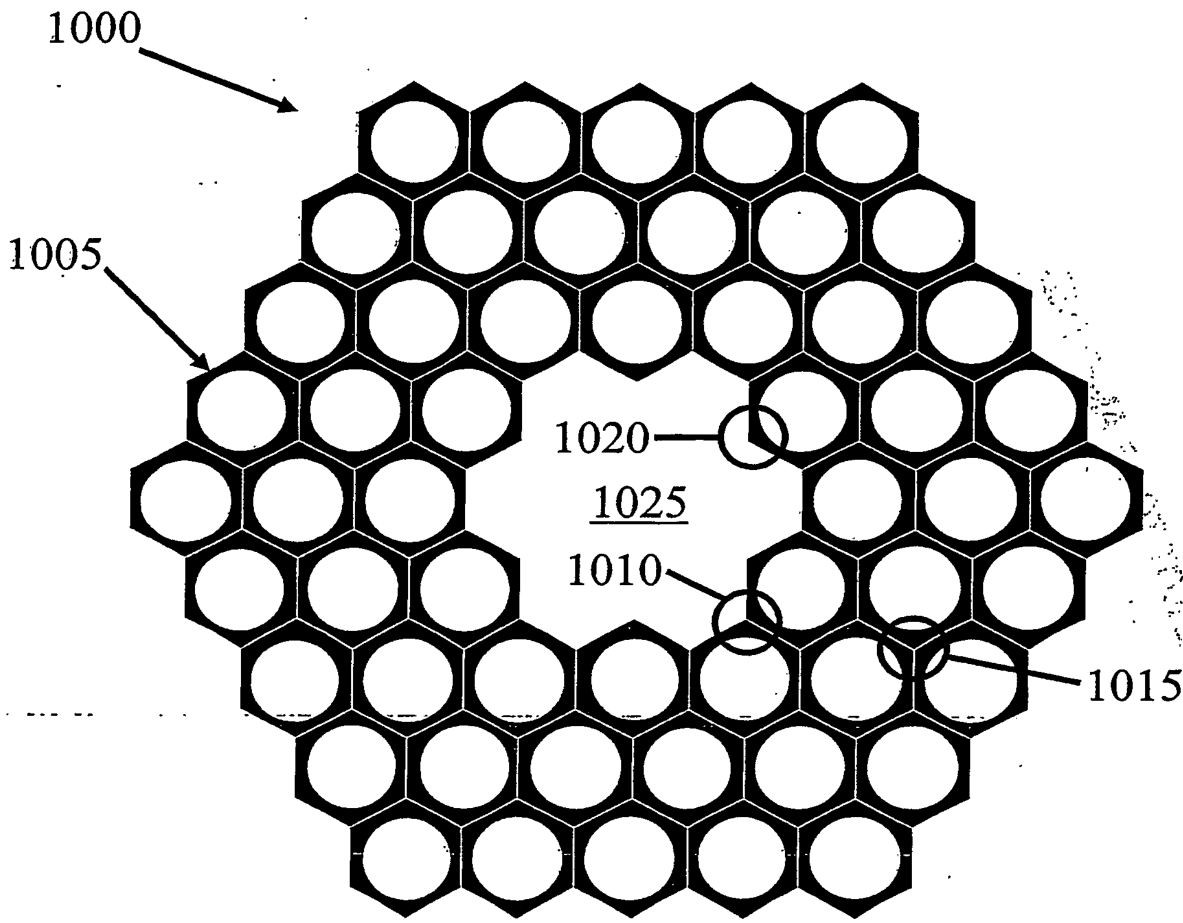


Figure 10

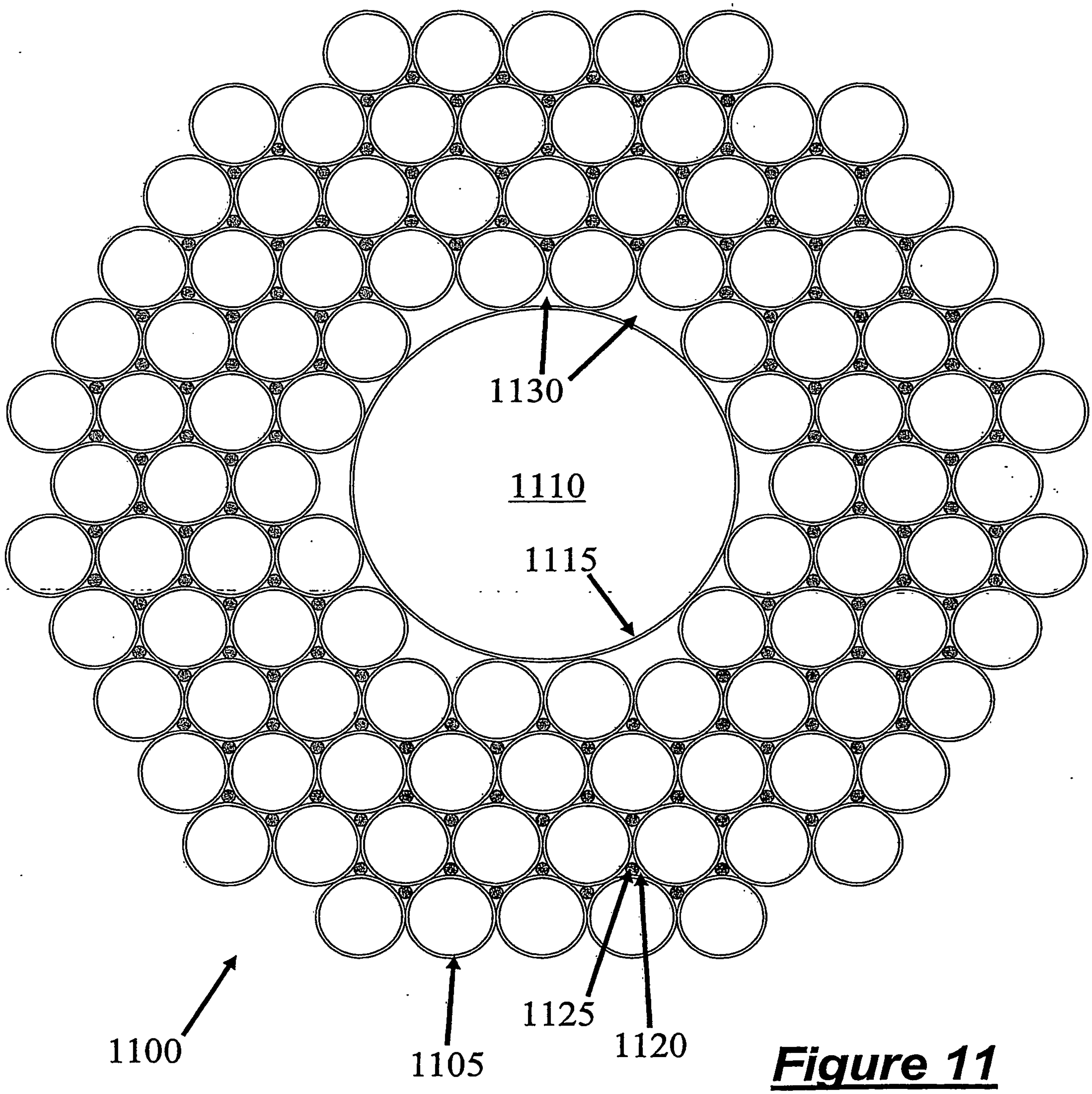


Figure 11

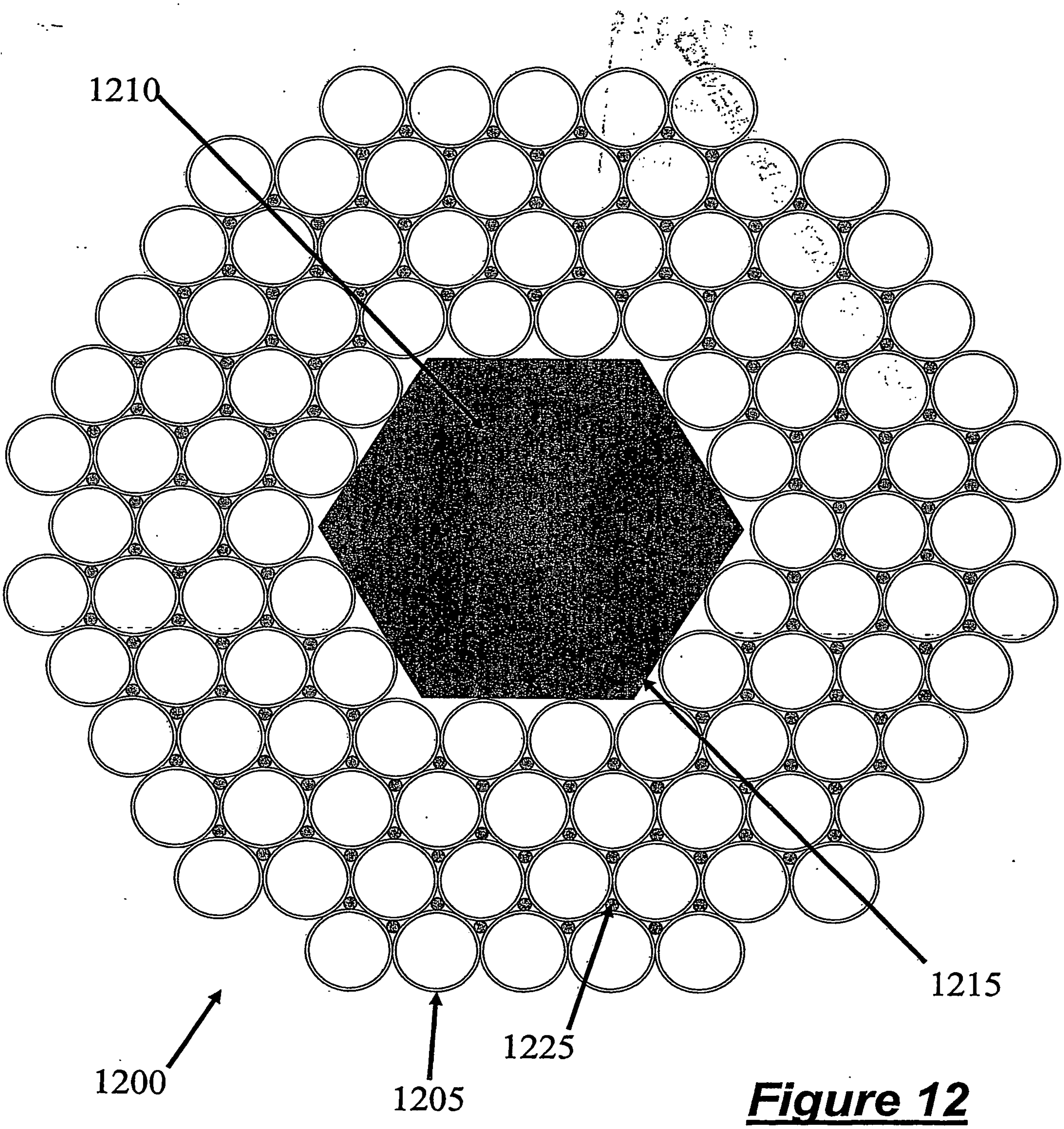


**Figure 12**